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MSc. (Eng) Research Thesis
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THE EFFECT ON THE DURABILITY PROPERTIES OF CONCRETE OF PARTIAL REPLACEMENT OF NATURAL FINE AGGREGATES WITH RECYCLED CONCRETE FINE AGGREGATES

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Date: November 2022

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Executive Summary

From the middle of the 20th to the beginning of the 21st century, natural resources for construction activities have been used for developmental activities such as urbanization, economic advancements, and population growth worldwide (Muigai, Alexander & Moyo, 2013). Currently, these factors have led to excessive exploitation of natural resources for use in the construction industry. UNEP (2014) reports that for each ton of cement production, the construction industry requires about six to seven tons of aggregates (sand and stone). On this basis, the global consumption of aggregates for concrete is projected to reach approximately 63 billion tons by 2024, rising from 43 billion tons in 2016.

Additionally, the exploitation of new natural sand deposits is becoming challenging. In most cases, these deposits are inaccessible for reasons such as challenging land utilization, environmental requirements, or the limitations of the reserve life spans. One of the ways to reduce this imbalance is to optimize the use of sand substitutes in concrete production (Chilamkurthy et al., 2016)

Muigai, Alexander and Moyo (2013) stated that South Africa had adopted blends of crushed rock and natural sand as a substitute for purely natural fine aggregates. Although these blends have proved to be a good solution for construction use in South Africa, the use of alternative resources such as Construction and Demolition Waste (C&DW) has been, to date, a major factor in assisting in dealing with this natural sand shortage.

However, the adoption of recycled fine aggregates has been a challenge due to their higher water absorption and lower mechanical properties and the variation of material sources, which is attributed to the lower durability performance of concrete made with recycled fine aggregates.

Regardless of these reported inferior characteristics of recycled concrete aggregates, the coarser fraction of 19 mm to 4.75 mm size fraction has been investigated as a potential alternative up to the 25% replacement level of RCA (Etxeberria, Marí & Vázquez, 2007; Kou & Poon, 2012; Duan & Poon, 2014; Thomas, Thaickavil & Wilson, 2018; Pacheco et al., 2019).

The RILEM specification for recycled aggregates deals with the coarse fraction of the material. Additionally, in the application of grade M25 and lower reinforced concrete structures, the Indian Standard IS: 383 allows up to 20% recycled concrete aggregates to replace the coarse fraction in concrete mixes.

This research focuses on replacing recycled fine aggregates (RFA) with a standard size of 4.75 mm and below by investigating the presence of a secondary reaction on the basis of further hydration from the adhered cement paste that may lead to better durability properties of the concrete mix. The investigation was conducted at three replacement levels (0%, 25%, and 50%) of RFA and two water binder ratios of 0.45 and 0.6. Most research on the use of RFA includes the addition of superplasticisers, mineral additives and extra water during mixing. None of these techniques were included during this research to form a basis of comparison and assist in understanding the use of RFA individually.

The experimental methodology for the study was conducted in three stages: material characterization tests, fresh and hardened properties of concrete. The gradation, fineness modulus, and particle relative density of all three types of fine aggregates used were measured during the material characterisation tests. A slump test was done to investigate the fresh properties of the concrete mixes, and a compressive strength test gave the mechanical properties of the concrete. The durability properties were investigated through Durability Index (DI) tests, accelerated carbonation tests, and bulk diffusion tests.

The results indicated that the blend of fine aggregates provided a standard and well-distributed particle size at the 25% replacement level. The particle relative density of mixes with RFA was lower than those of control mixes, attributed to the adhered cement paste on the surface of the RFA. For the slump test results, the lowest slump value was recorded at the 25% replacement level of RFA at 0.45 w/b ratio mixes, whilst for the 0.6 w/b ratio mixes, the lowest slump value was recorded at the 50% replacement level of RFA.

The compressive strength results for both w/b ratios indicated that for mixes with RFA, slightly higher or comparable compressive strength values were observed compared to concrete without RFA at 3, 7, 28 and 112 age of testing.

According to the criteria adopted for DI tests, all mixes showed an excellent quality of concrete during the Oxygen Permeability Index test despite having different replacement values of RFA. For the Water Sorptivity Index test, all results indicated a good quality of concrete except for the mixes with a 50% replacement level of RFA at the higher w/b ratio. The Chloride Conductivity Index test indicated that most of the mixes were of good quality and hence had comparable resistance to chloride penetration as natural aggregate concrete.

For the carbonation test, mixes with recycled fine aggregates showed no measurable carbonation at both testing ages compared to those without RFA at the 0.45 w/b ratio. For the

0.6 w/b ratio, mixes with recycled fine aggregates showed a lower degree of carbonation than mixes without RFA. During the bulk diffusion test, the 0.45 w/b ratio mixes illustrated that chloride ions depth had no significant variations from the control mixes after 120 days of exposure. At the 0.6 w/b ratio mixes, the control mix indicates a slightly lower chloride content at the surface but later, retains a comparable amount of chloride ions to the 25% and 50% replacement levels of RFA within the concrete matrix. These results indicate that at both replacement levels of RFA, the durability properties of concrete are comparable to the control mix.

The results also show that the recommended replacement level is 25%, which does not significantly affect the performance of recycled aggregate concrete mixes. Furthermore, when originating from a known source, with an average strength of 35 MPa, recycled aggregate concrete performs satisfactorily according to known mechanical standards and has comparable durability to natural aggregate concrete. Furthermore, this research work's success has implicated an economically feasible alternative resource in the construction industry.

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And lastly, I would like to thank my mother for believing and supporting me tirelessly throughout my master's journey.

List of Acronyms

C&DW	- Construction and Demolition Wastes
RFA	- Recycled Fine Aggregates
RCA	- Recycled Concrete Aggregates
ASPASA	- Aggregate and Stone Producers Association of South Africa
ITZ	- Interfacial transmission zone
DEA	-The Department of Environmental Affairs of the Republic of South Africa
SANS	- South African National Standard
USGS	-United States Geological Survey
CSI	- Cement Sustainability initiative
ASPASA	- Aggregate and Stone Producers Association of South Africa
C&DW	- Construction and demolition wastes
RCA	- Recycled coarse aggregates
RCCA	- Recycled concrete coarse aggregates
RFA	- Recycled fine aggregates
RILEM	- Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages
RH	- Relative Humidity
ASTM	-American Society for Testing and Materials standards
CEM	- Cement
SWR	-Standard Water Requirement
SANS	-South African National Standards
DI	- Durability Index

Table of Contents

List of figures

List of Tables

1 Introduction

1.1 Background

From the middle of the 20th to the beginning of the 21st century, natural resources for construction activities have been used for developmental activities such as urbanization, economic advancements, and population growth worldwide (Muigai, Alexander & Moyo, 2013). During this period, concrete has been the predominant material that has made the construction industry an economically viable industry to date. This factor is due to reasons such as the abundance of raw materials, the relatively low costs of processing and bulk transportation, as well as ease of exploitation of these naturally occurring materials for concrete production. These reasons have contributed to the extensive production and use of concrete globally (Bester, Kruger & Miller, 2017).

1.1.1 Concrete as a construction material

Concrete is a heterogeneous material comprising naturally occurring raw constituents: water, cement, and about 60 to 80 per cent by volume of fine and coarse aggregates. Of these, it is the cement that requires pyro-processing; other materials require relatively little processing and beneficiation. As previously discussed, there are several reasons why concrete has become one of the most commonly used resources in construction projects across the globe. In addition, the production of concrete has a low environmental impact per metre cubic basis. Generally, concrete only contributes to a higher global environmental impact because of the sheer volume of its application: vast quantities are used worldwide due to the widespread availability of concrete constituents (Karen Scsrivener, 2008).

Concrete aggregates fall into two size ranges: fine aggregate or sand (which is of < 4.75 mm size) and coarse aggregates (which are > 4.75mm size). Concrete aggregates are primarily used in concrete for their durability, strength, workability, and ability to accept smooth finishes. These aggregates may either be natural, manufactured, or recycled. The features of coarse aggregates, such as strength, maximum size, structure, and water absorption, affect the quantity of cement and fine aggregate used in a concrete mixture. Aggregates also influence the final concrete product's strength and dimensional stability properties (Alexander & Mindess, 2005; Radonjanin et al., 2013).

Additionally, 1 m^3 of concrete mix is estimated to contain almost 1 m^3 of aggregates (both coarse and fine) in terms of the loose bulk volume of aggregates. Thus, one way to approximately quantify the global use of aggregates is by monitoring cement production. UNEP (2014) reports that for each ton of cement production, the construction industry requires about six to seven tons of aggregates (sand and stone). On this basis, the global consumption of aggregates for concrete is projected to reach approximately 63 billion tons by 2024, rising from 43 billion tons in 2016. In addition, recent research by The Freedonia Group (2016) predicts global demand for construction aggregates of 51.7 billion metric tons by 2019, representing an annual growth of 5.2%.

1.1.2 The South African construction industry

Muigai, Alexander and Moyo (2013) stated that, South Africa had adopted a blend of crushed rock and natural sand as a substitute for purely natural fine aggregates. Although this blend has proved to be a good solution for construction use in South Africa, the use of alternative resources such as Construction and Demolition Waste (C&DW) has been, to date, a major factor in assisting in dealing with the adoption of alternative sources of fine aggregates.

As part of the solution for using construction and demolition waste as an alternative resource, the Department of Environmental Affairs of the Republic of South Africa DEA (2012) categorises waste generation. Their report stated that about 90% of waste South Africa's waste ends up in landfills. A total of 108 million tons of waste was reported in 2011, and about 98 million tons that made up for 90% of the total waste get disposed of in landfills. 59 million tons of this waste was classified as general waste, which constitutes construction and demolition waste, 1 million tons as hazardous waste, and the remaining 48 million tons as unclassified. The general waste composition comprises non-recyclable, recyclable, metals, organic, and construction and demolition waste. Out of these, construction and demolition waste fall under inert wastes, which comprise about 20% of total waste (DEA, 2012). Similar statistics have been reported by the GreenCape sector development agency (Barnes & Basson, 2016).

The availability of construction and demolition materials as a source for recycled concrete aggregates helps cater to the natural sand shortage. Recycled concrete aggregates have shown substantial potential in the construction of road layers in the transportation industry. Macozoma (2001) emphasized that the government needs to build awareness and make people understand that secondary materials do not necessarily mean "substandard" but have environmental benefits that need to be recognized and appreciated.

1.1.3 Consumption of fine aggregates and its impact on the industry

Common sources of construction aggregates for concrete production include rock quarries, alluvial sources, pit sands, and sometimes dune sands. Construction and demolition waste recycled as aggregates is growing in volume since it represents an additional source of readily exploitable aggregates. In Southern Asia, in India, concrete sand was initially primarily sourced from riverbeds and rock quarries; however, coastal and marine sources have been adopted due to declining inland sources (UNEP, 2014). It has been reported by Muigai, Alexander and Moyo (2013) that, currently, both coarse and fine aggregates are extracted from crushed rock for concrete production in the construction industry in South Africa.

Aurora et al. (2017) reported that about 11 billion tons of sand were mined in 2010 alone in the Pacific/Asia regions (UNEP, 2014; Torres et al., 2017). A statistical overview of sand demand reports that about 53 billion tons of material are mined globally annually (Chilamkurthy et al., 2016). The most substantial volume of solid material extracted (about 70 - 80%) is sand and gravel. Currently, the extraction of aggregates from rivers and marine areas affects the river and coastal ecosystems by increasing suspended sediments and causing erosion.

Since sand deposits within consumer vicinity are becoming scarce, long distances (over 80 km) covered by trucks transporting sand to demand zones significantly contribute to the increase in carbon dioxide emission into the atmosphere. The carbon dioxide emission also increases due to the high fuel consumption that the trucks have to cover. Zuo et al. (2018) highlight the difference between rail and road transportation of construction aggregates, showing that about 75% less carbon emission is decreased with the use of rail compared to the road transportation for aggregates transportation. Thus, Zuo et al. (2018) suggest reducing carbon dioxide emissions related to aggregates' transportation by adopting a spatial decision support system for minerals planning. The method employs a spatial interaction model to match aggregate production and consumption, then calculates the carbon emissions depending on mode and distance travelled, related to the movement of those aggregates.

The contribution to carbon dioxide emission from production and transportation is less significant as compared to cement production or other industries such as steel, as mentioned earlier. These reports are significant when dealing with the vast quantity of materials.

1.1.4 Construction and demolition waste

The Department of Environmental Affairs of the Republic of South Africa (DEA, 2016) suggests that the prevalence of a more sustainable construction market requires resource efficiency. Resource efficiency is the main factor that needs to be addressed while searching for measures to mitigate the increase of landfill sites and ways to dispose of this resource. One way to reduce this environmental challenge would be the use of recycled waste as an alternative material for concrete production. The recycled waste includes construction and demolition wastes as a source of aggregates for concrete production.

However, while the coarse fraction of recycled aggregates has shown a possibility of achieving similar mechanical properties to natural aggregates, the same has not been reported for the fine fraction of recycled aggregates because of their higher water absorption (Brown, 1998). Also, some research suggests that the achievement of high compressive strength when incorporating the coarse fraction of recycled aggregates is mainly associated with the original concrete compressive strength, which principally depends on the quality of the mortar and the interfacial transmission zone (ITZ) (Etxeberria, 2004; Etxeberria, Marí & Vázquez, 2007; Fathifazl et al., 2009). The fine fraction ($\leq$ 4.75 mm) has been given as the leading cause of the inferior characteristics owing to the greater proportion of adhered mortar associated with the smaller size of the aggregates.

1.2 Research focus

As one of the uses of recycled concrete in the form of recycled fine aggregates (RFA), this study aims to investigate the use of RFA as a fine aggregate source to produce concrete and to study the effects on concrete's mechanical and durability properties. This research addresses how to use RFA as a substitute for natural fine aggregates in typical concrete applications, thereby turning this so-called 'waste' into an available and affordable resource.

1.3 Problem statement

The exploitation of new natural sand deposits is becoming challenging. In most scenarios, these deposits are inaccessible for reasons such as: challenging land utilization, environmental requirements, or the limitations of the reserve life spans. Between 2011 and 2013, China reported more use of cement than the USA did in the entire 20th century. The widespread use of cement goes hand in hand with the consumption of sand for construction purposes (Chilamkurthy et al., 2016). The high use of these natural materials has led to recent challenges such as the depletion of sand deposits in countries such as China, India, Thailand, and Indonesia. Only second to China, India has been leading in its use of construction sand. It has also been one of the leading countries reporting on sand mafia and its associated risks to human lives and the construction industry in general. The lack of proper records and monitoring of sand extraction data contributes to the increasing challenge of environmental impacts caused by unequal amounts of the raw material to its use and renewal rate. As expected, a huge discrepancy exists between the issue's magnitude, the construction industry itself, and policymakers (UNEP, 2014). One of the ways to reduce this imbalance is to optimize the use of sand substitutes in concrete production (Chilamkurthy et al., 2016).

In a study by (2013) in the Western Cape, natural sand deposits located outside the Cape are limited due to their significant distances from the consumer market, making them a less economical option. Therefore, an alternative resource for sand is crucial to assist the future of concrete materials.

Recycled fine aggregates from construction and demolition waste provide an alternative resource as a substitute for sand. Also, not all concrete applications require high strength mix designs. For this reason, recycled concrete aggregates may be acceptable and fit for purpose. Meyer (2002) summarises that blending natural and recycled aggregates is commonly advisable, similar to other materials such as supplementary cementitious materials that are economically and technically sound.

The disadvantage to this possibility is that recycled concrete aggregates have been reported to exhibit high water absorption, lower mechanical and durability properties, and being perceived as waste instead of a valuable resource. Despite these findings, recycled fine aggregates have been used to make road pavements, low-rise buildings, and concrete slabs. These applications have moderate requirements for use (James Mackechnie & Munn, 2011; Sabai et al., 2013)

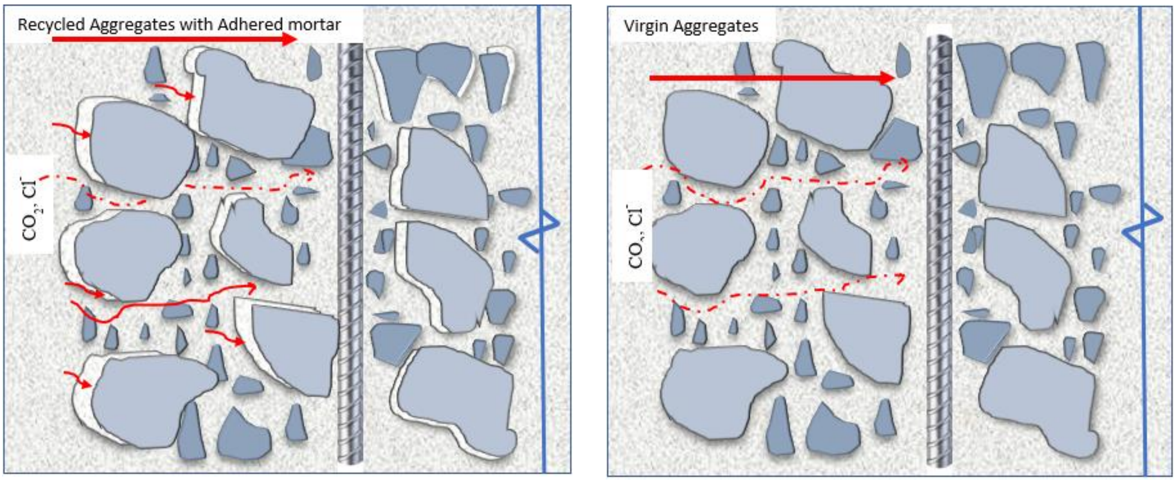
On the assumption that this material possesses potential benefits for concrete mixes, an investigation into the strength and durability properties of concrete made with recycled fine aggregates is necessary for in terms of

- The influence of utilizing recycled fine aggregates on the transport properties of concrete
- The reaction of aggressive ions with un-hydrated cement,
- Effects on durability properties due to the extra cement attached to the surface of the recycled fine aggregates, and
- Effects on strength due to their high-water absorption and the presence of adhered mortar are essential to determining this material's practicality.

1.4 Research hypotheses

This dissertation hypothesizes that the presence of adhered mortar on the surface of recycled fine aggregates is advantageous to the mechanical and durability effects on the overall concrete properties. Since cement undergoes continuous hydration in the presence of moisture, the higher water absorption property of RFA could potentially act as a source of water available for release after casting concrete. As part of the mixing water is taken up by the recycled fine aggregate during casting through the adhered cement paste layer, this water can be released into the matrix and further strengthen the concrete as the concrete matures, eventually improving the mechanical properties of the new concrete. Similar to mechanical properties, the presence of adhered mortar could provide extra mortar for aggressive ions to react with before reacting with steel or further penetrating the concrete matrix, hence allowing more time for deterioration to occur, as indicated in Figure 1-1: a) Transport pathways for virgin aggregates b) Transport pathways for recycled aggregates1.

Alternatively, the dissertation investigated whether using recycled fine concrete lowers concrete's mechanical and durability properties. This reduction of mechanical and durability properties may be due to the higher water absorption found in recycled concrete caused by the adhered mortar on the surface of the recycled aggregates.



a) Concrete matrix for concrete made with recycled concrete aggregates

b) Concrete matrix for concrete made with virgin aggregates

Figure 1-1: a) Transport pathways for virgin aggregates b) Transport pathways for recycled aggregates

1.5 Research aims and objectives

1.5.1 Aim

This research aims to investigate and evaluate the influence on the durability and other properties of concrete, of partial replacement of natural fine aggregates with recycled fine aggregates (RFA), in order to check the viability of RFA as an alternative resource for new construction projects.

1.5.2 Specific objectives

The investigation will be conducted on both mechanical and durability parameters for quality control measures of the concrete. Therefore, the following specific objectives will be investigated in order to achieve the main objective.

1. Assess the physical properties of recycled fine aggregates and identify an optimum replacement level of recycled fine aggregates for the concrete mix design and assess its influence on fresh concrete properties.
2. Investigating the transport properties (i.e., permeability, sorptivity, conductivity, and diffusion of both carbon dioxide and chloride ions) and behaviour of concrete made with different replacement levels of recycled fine aggregates
3. Determine the influence of different replacement levels of recycled fine aggregates on the overall durability of concrete, as well as a minor focus on the compressive strength of concrete

1.6 Scope and limitations

Three areas of application have been investigated in this work to understand how to partially replace natural fine aggregates with recycled fine aggregates.

- Characterization of both natural and recycled fine aggregates.
- The effects of strength are due to cement paste’s ongoing hydration adhering to the recycled concrete aggregates.
- Effects on durability properties of concrete through the presence of additional cement paste content in the recycled materials by investigating the carbonation and chloride ingress processes.

Recycled concrete was sourced from panels supplied to the laboratory for durability testing from a nearby national road expansion project, hence providing a 'real site' scenario. This source had the advantage of the concrete supplied being of fairly uniform composition and quality. It must be noted that the substitution of RFA aggregates is done only for the fine fraction at both 25% and 50% of the natural fine aggregates. Furthermore, no admixtures, supplementary cementitious materials or superplasticizers were used to modify the fresh properties of the concrete/design mix.

This research study was limited to:

- Compared to standard sources found in practical applications, recycled fine aggregates were sourced from a newly constructed project.
- All tests were conducted in the laboratory under standard environmental conditions.

1.7 Research significance

The practical significance and contributions of this research are.

- To address the sand depletion problem and reduce landfills consisting of concrete debris.
- To eradicate the perception that C&DW is just a waste and
- to add knowledge and, in the future, a basis of procedures and standards that would allow us to use recycled fine aggregate from C&DW as a useful resource in the construction industry.

1.8 Structure of the dissertation

This research study comprises five chapters. Chapter one introduces the main subject of the study, problem statement, research aims and objectives, as well as scope and limitations. The literature review is summarised in chapter two and presented in two parts. The first part is about concrete as a material, and the second part is about recycled concrete aggregates. Test methods and material characterization are summarised in chapter three. Chapter four presents the results and analysis of the experimental work in chapter three. Conclusion and future work are highlighted in Chapter five as well as any other additional recommendations.

2 Literature Review

2.1 Introduction

This chapter summarises the literature review provided for this research study. The review illustrates the use of concrete materials worldwide, the impact of concrete production and the depletion of natural found raw materials. It is reported that about 3 tons per year of concrete are used for each 7.7 billion people globally (Gagg, 2014). The over-exploitation of natural resources for concrete production has increased the possibility of these materials becoming exhausted because of the high volume of concrete production as the principal building material in construction projects. In addition, concrete production has increased the amount of construction and demolition waste generated in the construction industry. Hence, this review highlights the use of recycled concrete aggregates as an alternative resource for natural aggregates from both a concrete mechanical and durability aspect.

Similarly, a summary of the properties for both natural and recycled concrete aggregates is highlighted as well as a contrast between the properties of concrete made with natural aggregates and recycled concrete aggregates. These properties highlight the contrast between recycled concrete aggregates and natural fine aggregates, leading to the significance of the research work. And lastly, this review emphasises the objectives of the study and research conducted in the experimental investigation chapter.

2.2 Concrete use and impact in the construction industry

Currently, over 50% of the world's population resides in cities, which influences the rise in developmental activities in the construction industry, such as building urban centres, infrastructural advancements and residential buildings to accommodate the growing population (Walker & Alexander, 2013). These activities produce the highest amount of construction waste, often disposed of in underdeveloped land or a landfill, posing potential environmental risks. Oikonomou (2005) summarises the ecological issues associated with construction as follows: 50% of raw materials exploited from natural sources consume about 40% of total energy from the production process, transport and use of the raw material and generally produce about 50% of the total construction waste that ends up in landfills. Adesina (2020), on the other hand, reports that most of the carbon dioxide emissions from the concrete industry come from the manufacture of Portland cement, which is the principal binder in concrete, as well as material transportation from vehicle emissions.

Due to rapid urbanization, the demands on civil infrastructures, such as investment in public transportation and infrastructure for non-motorized alternatives, might lower the demand for private automobiles while encouraging higher-density development. On the technology side, a growing dependence on information and communication technology and "smart buildings" that regulate themselves to decrease energy usage, as well as transportation networks that monitor themselves to avoid traffic congestion, need improvement to accommodate population growth.

As increasing volumes of materials are being extracted from natural resources and used to build cities and urban infrastructure, waste production is essential. According to estimates by Atcin in 2000 and CEMBUREAU in 2011, global concrete usage increased steadily from 6.4 billion m^3 in 1997 to 8 billion m^3 in 2009, respectively. Meyer (2002) reported that about 10 billion tons of concrete are used globally, while Monteiro (2006) reported 11 billion metric tons per year of concrete consumption globally in 2006. In the same year, the Global Cement and Concrete Association (GCCA) reported that approximately 25 billion tons of concrete were produced annually (Klee, 2009a), surpassing the 8 billion m3 reported by CEMBUREAU in 2011. Gagg (2014), on the other hand, indicated that concrete is the most consumed material, with about 3 tons per year used for each 7.7 billion people in the world. The large consumption of concrete is the major reason why certain parts of the world run the risk of natural resource depletion because the significant constituents of concrete are naturally non-renewable, and thus they run a risk of depletion (Walker & Alexander, 2013; TheEconomist, 2017).

Concrete is made by mixing non-renewable materials that occur in nature; hence, their over-exploitation results in the depletion of these materials (Walker & Alexander, 2013). In South Africa, concrete production between 2005 and 2008 averaged about 18.9 million m^3 annually (Muigai, Alexander & Moyo, 2013). These massive quantities necessitate significant amounts of natural resources for aggregates and cement production.

Research by Meyer (2002) has reported that one of the tools and strategies to implement on the detrimental effect of concrete use is an increased reliance on recycled resources. Since aggregates constitute about 60 -70% of the concrete mass, an effective strategy for recycling will lift the burden on the demand for natural materials. Recycling these raw materials reduces carbon dioxide emissions to the atmosphere and the exploitation of resources from the production of cement and transportation distances. As the world is advancing towards a sustainable future, a closed-loop life cycle is required in the construction industry. That is, from the construction stage, maintenance stage, demolition stage and recycling of building materials stage, to adjust these emissions across all construction practices globally.

2.3 The use and effect of concrete constituents in South Africa

In South Africa, the Department of Minerals and Energy (DME) summarises that the construction industry contributes to about 4% of the gross domestic product in the country (Motsie & Malematja, 2014). The Aggregate and Stone Producers Association of South Africa (ASPASA) recorded about 39.7 million tons of raw materials used for concrete production between 2005 and 2008 (Muigai, Alexander & Moyo, 2013). This quantity is projected to be only around 30% of total aggregates and sand extraction; the remaining is utilized for non-concrete uses such as mortars, plasters, and road construction. To further classify this quantity, the number of aggregates was 32.1 million tons and 7.6 million tons for the various binders used for concrete production. These quantities illustrate that over 80% by mass of both coarse and fine aggregates is utilized for concrete production.

In the South African sand and aggregates industry review, Motsie & Malematja (2014) reported that suitable quality aggregates found in nearby deposits at lower costs had been subjected to overexploitation, resulting in depletion of the sources. New sources of sand deposits in the outskirts of cities and towns had to be discovered, resulting in higher transportation costs. Furthermore, they highlight that to produce a wide range of particle sizes of aggregates, the original texture of the rock and degree of physical and chemical weathering is important in various regions; hence over-exploitation from one source raises a higher risk of nearby depletion of aggregates sources.

Similarly, the DME (DME, 2008) showed that the annual production capacity of sand and aggregates used in the construction industry from 2006 to 2016 would grow at an average yearly rate of 1.5 per cent from 2008 to 2016. Hence, it is critical to address the possibility of natural components of concrete becoming exhausted because of the high volume of concrete used as the principal building material in construction projects. According to these statistics, concrete materials and their broad applicability for various constituents pose a potential need to be investigated and understood.

2.4 Concrete and its constituents

Concrete is, by far, the most important and widely utilized construction resource in the world (Meyer, 2002; Alexander, Bentur & Mindess, 2017). It is versatile and consists of chemically unreactive substances that can be designed into various shapes and sizes when combined. Its constituents are vastly available in their natural forms, can be designed to meet any strength requirements, allows an adjustable surface according to the natural environment and, importantly for this research, allows for the use of recyclable materials. Due to these applications, concrete has been the sufficient material used for construction since ancient Roman, Egypt and civilisation times. The ability of natural pozzolans to bind stone, sand and water has been worldwide adopted for the construction of even modern-day structures. During the course of time, admixtures and additives such as air entrapping agents have been added to increase the concrete's resistance to severe environments and its durability. This allowance of versatility has reinforced the importance of designing concrete with a new durability approach (Alexander, Bentur & Mindess, 2017).

Concrete is mainly made up of cement, primarily composed of calcium oxide (lime), coarse aggregates, fine aggregates, and water. Over the years, this combination has been optimized to achieve the most suitable mix design for construction purposes. Since the early Romans age, the technology of using cementitious material to bind aggregates in concrete has been perpetuated. The Pantheon structure in Rome is one example of concretes' durability (Schiessl, 1996). Various mix designs are currently achieved due to this set-out procedure. In South Africa, this procedure is provided under the South African National Standard (SANS) SANS 5861-1:2006. Several kinds of materials have been substituted to this mix to meet the performance of the concrete environment on the actual structure.

In developing this technology, steel reinforcement was introduced to provide tensile strength under the realization that it will never corrode while embedded in concrete (Schiessl, 1996; Alexander & Mindess, 2005). While reinforcement was primarily incorporated to provide tensile forces, it also prevents concrete from spreading. This invention made concrete long-lasting and durable, especially on the concrete members subjected to tensile strength.

The introduction of additional mineral additives or cementitious materials, i.e., fly ash, ground granulated blast furnace slag, and silica fumes, are used to adjust the performance of concrete while maintaining its durability. These supplementary cementitious materials replace a significant amount of Portland cement; hence, they have been found to bring about various advantages such as i) sustainable development due to reducing the over-exploitation of natural resources that are fast depleting, and ii) low energy emission associated with lower carbon dioxide and green gases emissions (Corinaldesi & Moriconi, 2009; Angelucci et al., 2017).

Recently, the use and constituents of concrete are changing due to increasing human needs, such as ever-changing infrastructural demands that affect the economy and sustainable development as well as advancement in concrete technology (Adesina, 2020). Currently, the structures' performance and durability have been crucial in making concrete structures last longer in aggressive environments. The wide availability and lower costs associated with concrete components play an essential role in retaining its usage over the years. For that purpose, it is necessary to consider these natural resources individually to cope with their subsequent effects.

2.4.1 Cement

Cement is an inorganic, non-metallic material with hydraulic binding properties, commonly used as a bonding agent in construction. It is a fine powder, greyish in colour, made of largely calcined lime of about 60-65%, and clay and other ingredients such as silica, alumina, iron, magnesia, calcium sulfate, sulphur and alkalis; that when mixed with water, tends to hydrate to cement paste. In the presence of fine aggregate (sand), it forms mortar, and while in the presence of water, sand and gravel, it forms concrete (Anthony J. Buonicore & Davis, 1992).

In the SANS 50197-1:2000, Cement or binder material is referred to as a Portland clinker, granulated blast furnace slag, pozzolanic materials, fly ash, burnt shale, limestone, and silica fume as the main constituents of ordinary cement (Graham Grieve, 2009). Most of these constituent rocks are found insufficient amount across several countries. The United States Geological Survey (USGS) Mineral Commodity summarises that in 2019 about 4 billion tons of Portland cement were used in construction projects worldwide, as seen in Figure 2-1 (United States Geological Survey, 2020). As attributed to the large cement production, F.Birol (2018) reports that the cement industry contributes to about 7-8% of the global carbon dioxide emission in the world. This factor makes the cement industry the third-largest industrial energy consumer globally, contributing about 10.7 exa-joules per year. Cement production requires the breakdown of limestone, which accounts for around two-thirds of total carbon dioxide emissions, with fuel-burning accounting for the remainder. Furthermore, it is estimated that manufacturing one ton of Portland cement generates approximately one ton of carbon dioxide into the environment.

Cement production releases carbon dioxide gas in two aspects: clinker processing emissions and energy or fuel combustion emissions. First, during the cement clinker production process, which is the chemical reaction originated from the main components. This process produces oxides by decomposing limestone as carbonates, largely $CaCO_3$, into oxides (lime, CaO) and carbon dioxide gas under heat (Olivier, Greet Janssens-Maenhout & A.H.W., 2014). Depending on the amount of lime produced, a directly proportional amount of carbon dioxide is released. Secondly, the combustion of fossil fuels to have the energy required to burn the raw ingredients (clinker) adds up to about 60% of carbon dioxide from the process emissions. In combination, the total emissions from the cement industry are estimated to be 8% of total global CO_2 emissions (Andrew, 2017).

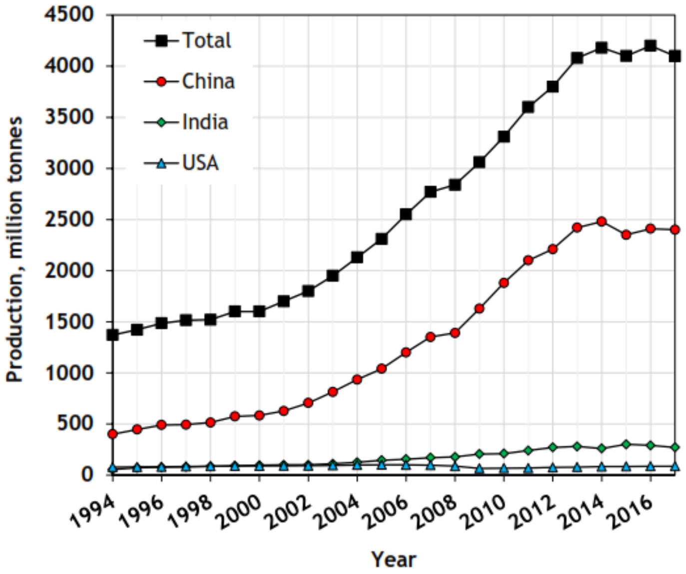


Figure 2-1: An illustration of the global cement production in 2016 (United States Geological Survey, 2020)

2.4.2 Water

Mixing water has various roles in concrete. One of the significant roles of mixing water in the concrete mix is to influence the hydration of cement to release hydration phases responsible for strength provision. A mixture of cement and water provides a cement paste that is freshly workable and can consistently bind the rest of the concrete constituents. The amount of water required for batching during concrete mix design includes free moisture present on the surface of aggregates, water added during delivery of concrete mix, and any amount of water required for the addition of admixtures. It should be noted that water absorbed by aggregates is not included as mixing water because it is not readily available for the workability of the concrete (NRMCA, 2017). In practice, water appropriate for human usage can be used as mixing water.

Water quality is of concern for making concrete, and using uncontaminated and potable water to produce concrete is highly recommended. Suppose non-consumable sources of mixing water such as wash water, stormwater and local found streams are used. In that case, qualification tests should be conducted to investigate their impact on the concrete mix (Reddy Babu, Madhusudana Reddy & Venkata Ramana, 2018). These tests are performed because mixing water can affect the setting time and strength development. In the presence of aggressive ions, water can facilitate reinforcement corrosion and hence early concrete deterioration (John Goodman, 2009).

2.4.3 Aggregates

By definition, aggregates are sand or stone particles formed as a result of natural disintegration of rock or extracted by mechanical procedures of either crushing or milling of rocks (Graham Grieve, 2009a; SANS3001-AG1, 2009; SANS 1083, 2017). They are mineral constituents of concrete found in granular or particulate forms, comprising coarse and fine fractions (Alexander & Mindess, 2005). Finer fractions are classified as the sand of particle size of at least 90%, passing the sieve with a square aperture of 4.75 mm nominal size and retained on a sieve with a square aperture of 75 µm nominal size. And the coarser fraction is defined as the stone of particle size retained on a sieve with square aperture 4.75 mm nominal size.

Aggregates are the principal constituents of concrete forming both the fine and coarse portions. They make about 60-80 per cent by volume of the concrete mix. They are the main reason concrete is sufficient for engineering purposes, such as strength provision through load support and durability through environmental protection (Ozbakkaloglu, Gholampour & Xie, 2017). As a surplus to being an economical filler, due to their lower cost in production compared to other constituents, their large per cent by volume contributes to their significant importance in concrete production. And its extensive uses and applications affect our daily life environment through infrastructural development and residential shelters (Mindess, David & Young, 2003). (2013) concluded that coarse and fine aggregates account for 61% by mass of the total raw materials consumed per year during concrete production from 2005 to 2008. The national statistics of the United Kingdom reported that about 63% of the primary aggregates sold were used for concrete production in 2014 (Highley et al., 2019).

The relation between the properties of aggregates and their concrete performance must be fully understood before being utilized in concrete practices. For most concrete applications, aggregates must meet the minimum standard requirements, i.e. cleanliness, strength, durability and free from contaminated species (Alexander & Mindess, 2005).

Aggregates exist in various moisture states that predominantly affect the properties of hardened concrete, such as density and strength. These moisture states include oven-dry, air dry, saturated surface dry and damp conditions. Oven dry has no moisture, and the aggregates can absorb to their full potential received water. Air dry is the state of excess air pores in the aggregates; hence, a small amount of absorption can fill in the pores. Saturated surface dry is when the pores are saturated, but the surface is dry; therefore, no water exchange occurs from or to the aggregates.

On the other hand, a damp state is when the aggregate contains an excess of free water in its matrix (Alexander & Mindess, 2005), see Figure 2-2. It is also reported by (Poon et al., 2004) that the moisture states of aggregates impact the workability and uniformity of concrete mixes and therefore affect the hardened properties of concrete. Their work investigated the influence of air-dried, oven-dried and saturated surface dried conditions of natural and recycled aggregates on the properties of fresh and hardened concretes. Compared to concrete with natural aggregates, he states that at 50% and less replacement value of recycled concrete aggregates that are air-dried, fresh concrete's workability and the hardened concrete's compressive strength remains unchanged.

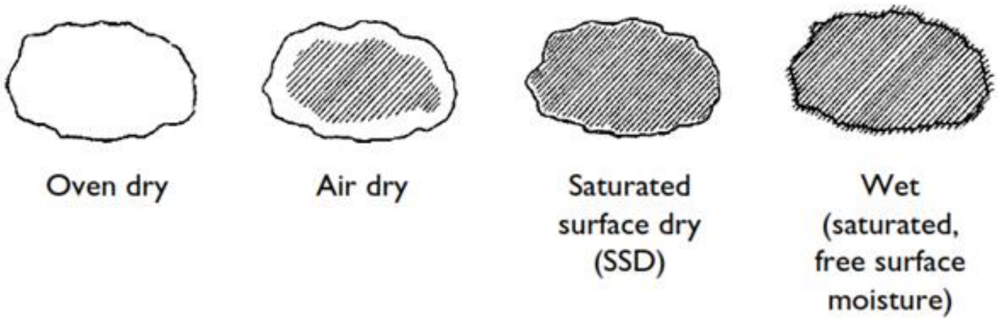


Figure 2-2: Different moisture states of aggregates (Alexander & Mindess, 2005)

Of importance to this research is the fact that recycled concrete aggregates have a high-water absorption capacity, and hence the effect of the recycled aggregates' moisture states on the characteristics of fresh and hardened concrete made using recycled aggregates is an important aspect to address.

There are various types of aggregates found in different places in South Africa. In the Western Cape, Cole, Ngcofe & Halenyane reported that about 32 out of 76 working pits and 150 out of 239 dormant pits are composed of building sand. This data was collected and updated till 2013. The sand in these pits is rich in quartz minerals and has an insignificant amount of organic material and chloride content. Construction sand from these pits is mainly utilised for construction applications because they are about 80 km from the construction/building site, making them economically viable. Various types of sands are found in the Western Cape, such as Cape flat sands, west coast sand, and Malmesbury-Klipheuwel sands. However, only Malmesbury or Klipheuwel sands and greywacke crusher sands are discussed in this study.

As the name infers, Malmesbury, or Klipheuwel sands, is located in the Malmesbury-Klipheuwel area and consists of siliceous pit sands such as colluvial and hill wash sands. The sand particles are originally round-shaped and comprise continuous grading. Despite their high fine contents of 20% less than 0.150 mm and 15% less than 0.075 mm size, they produce a higher quality of concrete with water requirements as low as 170 l/m^3 (Graham Grieve, 2009). These sands are made up of aeolian sands initially found in the dunes of Cape Flat regions. However, Walker & Alexander (2013) observed that this sand presented challenges when utilised in concrete mixes. They observed low workability and stickiness of the mixture in the fresh state and high organic content in the hardened condition, which caused the hydraulic reactions that influenced the concrete hardening to be retarded.

Large bedrocks are crushed for the greywacke crusher sand to obtain crushed aggregates, and a substantial quantity of fine aggregate remnants are produced. These massive fine remnants are so-called crusher sand, which forms another primary source of sand in the construction industry. Greywacke crusher sand provides a viable solution for the limited supply of concrete aggregates from natural sand sources. In the Western Cape, the rock sources used for crusher sand are Cape Granite Suite, Table Mountain, and Malmesbury group, which produce granite, quarzitic sandstones and greywacke sand, respectively (Walker & Alexander, 2013). This fine concrete aggregates or greywacke crusher sand is typically angular and flaky in shape and comprises a partial gap graded distribution (Walker & Alexander, 2013). This gradation is a consequence of the crushing process; thus, suitable crushing methods are needed to ensure more acceptable properties for concrete use.

Reports from AfriSam highlight that crusher sands are durable and comply with the strength and standard water requirements of approximately 180 to 185 litres per cubic metres (Walker & Alexander, 2013). However, due to its high production cost compared to natural sand and the partial gap gradation, the individual use of greywacke crusher sand in concrete is considered not economical. The production process of sand and aggregates is summarised in the Figure 2-3. The combination of both dune sand with greywacke crusher sand provided an adequate blend of continuous particle size and shape to be utilized in construction activities (Graham Grieve, 2009b). Figure 2-3 illustrates the production process of aggregates found in South Africa. The procedure demonstrates how optimization of blended aggregates is included in aggregate production.

There are three categories of aggregates classified in the following section. However, only natural and recycled aggregates are extensively discussed since they are the primary focus of the research work.

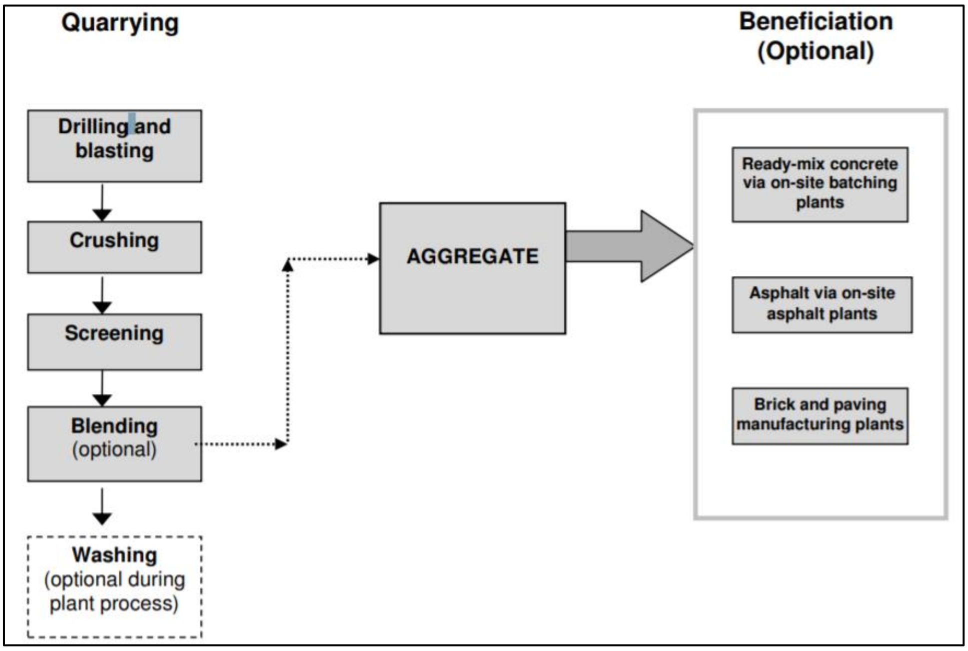


Figure 2-3: The production process of sand and aggregates in South Africa as summarised in (Motsie & Malematja, 2014)

2.4.3.1 Classification of aggregates

Construction aggregates can be classified into three broad categories.

- Natural occurring aggregates
- Manufactured aggregates
- Recycled concrete aggregates (rubbles) from construction and demolition wastes

Naturally occurring aggregates are formed after physical disintegration or various chemical weathering processes of rocks. These occur in their natural state and are applied into construction in their natural forms (Walker & Alexander, 2013). Their rock source, moisture state and degree of physical or chemical weathering determine their range of particle sizes. Naturally, they are sourced around rivers, beaches, dunes and in between mountains areas. These sands consist of alluvial, aeolian or windblown and marine or beach sands (DME, 2008). In South Africa, three main types of rocks are used for construction aggregates, as shown in Table 2-1.

Table 2-1: Types of rocks forming coarse aggregates as summarised by (Motsie & Malematja, 2014)

Type of rock	**Example of rock**
Igneous rocks such as	aandesite, basalt, dolerite, felsite, gabbro, granite, granodiorite, norite, rhyolite and syenite
Metamorphic rocks such as	Granite-gneiss, granulite, hornfels, quartzite and slate
Sedimentary rocks such as	Quartzite, sandstone, greywacke, shale and tillite

Manufactured aggregates are products of mechanical crushing processes or milling of natural rocks into desired sizes for construction. In addition, as a waste from the mining industry, the mine sand can be classified as manufactured sand (DME, 2008). Recycled concrete aggregates (Rubbles) are produced by demolishing buildings, removing and fracturing existing concrete to a suitable dimension and later separating the concrete from other construction and demolition wastes. Recycled concrete aggregates can be crushed into desired sizes for reuse (Walker & Alexander, 2013). It should be noted that recycled concrete aggregates are the main focus of investigation in this study.

The following section summarises recycled concrete aggregates from construction and demolition wastes, their origin, the importance of recycling, the use and associated challenges of utilizing recycled concrete aggregates, the various treatment methods, and lastly, the demand for recycled concrete aggregates in construction activities.

2.4.3.2 Impact of aggregate on concrete properties

The type of aggregates used in concrete can profoundly affect the physical, mechanical and durability properties of hardened concrete (Grieve, 2009). Aggregates make concrete fit for its intended purpose. They provide volumetric stability, lower deformations due to moisture and creep, lenience to thermal movements, resistance against erosion and abrasion, as well as strength (Alexander & Mindess, 2005).

In terms of concrete durability, aggregates play a major role in the time taken for the deterioration processes to occur. For instance, reactive aggregates can accelerate the process, while non-reactive aggregates decelerate the process. On the other hand, porous aggregates influence the ingress of aggressive substances into the concrete matrix and vice versa (Graham Grieve, 2009b). Also, unsaturated porous aggregates can reduce the mixing water during concrete preparation; as a result, a poor interfacial transition layer leads to a weak bond of aggregates with other constituents, which can affect the performance of concrete in the long term. However, this same concept of water uptake can explain a different cause of secondary strength increase in concrete by providing a concealed source of water to the concrete after initial hardening has fully developed. The water uptake can, later on, seep into the hydrating matrix, increase strength development, and reduce long-term shrinkage (Alexander & Mindess, 2005).

2.5 Construction and demolition waste (C&DW)

The concept of recycling concrete has been investigated since the culmination of the Second World War in 1945. After the destruction caused by the war, many buildings were left ruined, and so civil engineers needed to build and find ways of dealing with the large stock of construction waste or "rubble" (Vitruvius Marcus Pollio [Morgan], 1955). This incident generated interest in using recycled wastes in subsequent years. However, natural materials have been abundant for many years, and so this interest was not of major importance at the time. From the World War II period until recent years, the construction industry has generated an enormous amount of C&DW, which is reported to be about 35% of the solid waste in the world (Llatas, 2011). For instance, in 2008, it was estimated that nearly 890 million tons of

C&DW were generated per year in Europe only (Saez et al., 2013). In France alone, by 2012, about 260 million tons of C&DW were being produced annually and about 15 million tons in Belgium alone in 2016 (Bouarroudj et al., 2019). Unfortunately, most of it still ends up in landfills in unprecedented areas.

The Department of Environmental Affairs (DEA) of the Republic of South Africa defines general wastes as wastes that do not cause any hazardous effects or threaten human health or the environment (DEA, 2012). They generally include domestic, inert, commercial, and construction and demolition waste. Construction and demolition wastes (C&DW) are general wastes generated during construction, alterations, repair and rehabilitation, and demolition of a built-in structure or a physical infrastructure (DEA, 2012). These wastes include concrete debris, earth, rock, plastic, ceramic, masonry, metal, asphalt, and wood displaced during the construction process. Construction and demolition wastes originated from residential and non-residential high- and low-rise buildings and dense housing projects. According to the DEA (2012), construction and demolition wastes are estimated to be about 20% of general waste, and about 16% is recycled.

Various factors have contributed to the increase of construction and demolition wastes. These factors include the end-of-life cycle of multiple buildings, concrete pavements, other structures with structural deterioration beyond repair, structures that do not serve present-day needs and requirements, structures unable to withstand natural disasters and new construction for economic growth and social development.

The DEA (2012) report summarises that about 90% of waste, equivalent to 98 million tons generated in South Africa, ends up in landfills. Fifty-nine million tons of this waste is classified as general waste (which makes up for construction and demolition waste), 1 million tons of the waste is classified as hazardous waste, and the remaining 48 million tons remain unclassified, which makes up a total of 108 million tons of waste in total. According to the report, out of the 59 million tons of general waste, only 5.9 million tons (10% of the general waste) get recycled. The remaining 53.1 million tons are ultimately disposed of in landfills. Similar statistics have been reported by the GreenCape sector development agency (Barnes & Basson, 2016).

In Sub-Saharan African countries, it is reported that about 174 million tons of general waste were being generated in 2016 at a rate of 0.46 kilograms per capita per day. And about 69% of the general wastes were being openly dumped in landfills, as reported in the Urban development series published by the World Bank Group. Global construction waste is also expected to nearly double to 2.2 billion tons by 2025 (Kaza et al., 2016). Construction waste is estimated to consist of half of the solid waste generated annually in this period.

In addition, part of the challenge in adopting construction and demolition wastes is the limited amount of published materials that estimate the amount of construction and demolition wastes on the ground. Henceforth while the global demand for aggregates is rising, the importance of recycling concrete debris is not fully utilized.

Other than the lack of clear standards, codes and published material, the variability in the source of recycled aggregates similarly accounts for the challenge in its adaptation for structural and non-structural purposes. This variability has been a challenge due to the high investment in different recycling equipment required to sort out the large variability in material quality (Muigai, Alexander & Moyo, 2013; Tam, Soomro & Evangelista, 2018).

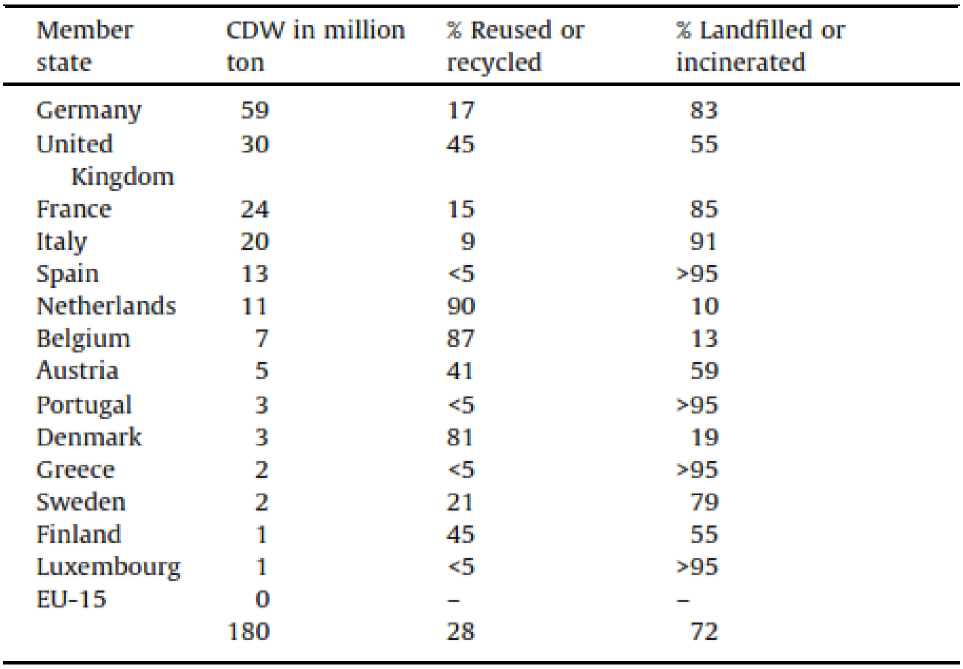
2.5.1 C&DW generation and the importance of recycling

Waste generation is an unavoidable concept. And as long as there is growth in human interactions (such as the movement of people from rural to urban areas), population growth and activities (such as technological advances), waste generation will continuously be propagated. After years of using natural resources for construction purposes, construction and demolition waste disposal has become an unsustainable practice. Matias et al. (2013) summarised the quantity of C&DW production across Europe as seen in Table 2-2 from the Symonds group. With an estimated 180 million tons of C&DW produced, only 28% of it is reused, and the rest is taken to landfills or incinerated.

Recycled concrete aggregates are derived from various sources; demolished old concrete buildings, fresh concrete rejected batches, and precast elements are the most common materials. These materials are part of C&DW separated into only concretes' main constituents (cementitious materials, fine and coarse aggregates, and water) that can be reused in new construction. In several countries, the production of C&DW has illustrated the potential to contribute significantly to the environment and economic sectors. In 2017, the Department of Environmental Affairs of the Republic of South Africa (DEA) estimated about 5.36 million tons of builders' rubble is generated in South Africa annually. However, according to the Market Intelligence Report by (GreenCape, 2020), this amount could be as high as 8.7 million in 2017 and 9.0 million in 2018, based on the amount of waste quantified at the Cape landfills and the Gross Domestic Product for the Western Cape province region (GDPR) statistics. Additionally, the report summarises that waste generation and recycling activities in South

Africa, as is in contrast to other parts of the world such as Japan, Europe, and the Netherlands, are driven by market demand and not incentives such as higher landfill fees and taxes on the extraction of natural materials.

Table 2-2: Amount of C&DW produced across Europe by (Matias et al., 2013)



Member state	CDW in million ton	% Reused or recycled	% Landfilled or incinerated
Germany	59	17	83
United Kingdom	30	45	55
France	24	15	85
Italy	20	9	91
Spain	13	<5	>95
Netherlands	11	90	10
Belgium	7	87	13
Austria	5	41	59
Portugal	3	<5	>95
Denmark	3	81	19
Greece	2	<5	>95
Sweden	2	21	79
Finland	1	45	55
Luxembourg	1	<5	>95
EU-15	0	–	–
	180	28	72

Concrete recovery or construction and demolition wastes to yield new concrete has been reported to have various advantages. The substitution for natural resources and the added environmental costs of exploiting a natural resource is reduced. It reduces excessive landfills of re-usable materials that can be recovered and used in the construction industry and supports green building goals such as the Leadership in Energy and Environmental Design (LEED) rating system. In some instances, employment opportunities arise in the recycling industry that would not otherwise exist in other sectors (Klee, 2009). More labour is included in the sorting and diverting stage in the recycling industry. Although there is a substitution of labour for energy during the handling and sorting of the material, the use of recycled aggregates necessitates less energy in the production process, thus reducing the product's embodied energy. The Market Intelligence report by GreenCape (2020) summarises that in the City of Cape Town, it costs approximately 1.3 to 1.7 times on average to use natural aggregates than to adopt recycled aggregates.

In terms of logistics costs, the recovered aggregate being generated and made available closer to the point of application reduces these costs than the generation of natural aggregates, typically transported from outside urban centres. Additionally, concrete recovery reduces transportation costs due to being able to recycle concrete during demolition or at construction sites where it can be used as a source of supply.

Recycling concrete rubble evades tax fees and costs of dumping materials in landfills. Furthermore, it provides good performance and preventive measures for some applications due to good compaction, density, and high-water absorption properties, such as road sub-base applications and colder regions. A partial replacement of natural aggregates with recycled aggregates provides a competitive option for using sustainable alternatives in construction materials.

2.5.2 The use of recycled concrete aggregates in the construction industry

It has been reported that the most efficient way to utilize C&DW is by crushing it and adopting it on local-based constructions in order to maintain a stable supply around major urban areas (ECO-SERVE, 2004). As illustrated in Figure 2-4, the crushing process is done to obtain the standard concrete aggregates for gradation purposes and sufficient quality and performance. Due to its material composition, its sources are abundant in our living spaces. In Roman times, concrete was made by incorporating rubbles or demolished bricks and stones. It is also reported to be used for building foundations and walls during these times (Vitruvius Marcus Pollio [Morgan], 1955).

Buck (1976) summarises that World War II had created an excessive amount of demolition material; hence there was a rising need to discard the material and reconstruct Europe. Later on, in the 1970s, he also records that the United States adopted the use of RCA for non-structural applications such as basecourse and fill materials. His research also reported that secondary concrete would have higher water absorption and result in lower concrete strength at the same water-binder ratio and workability than concrete made with comparable virgin aggregates. And he further explains that concrete made using recycled aggregates showed an improved frost resistance due to their ability to store extra water and release it to the concrete matrix after a while, compared to concrete made with virgin aggregates. A concept which forms the basis of this research is the durability aspect.

Over the years, the utilization of C&DW as recycled concrete coarse aggregates (RCCA) has been a promising technology with regard to mechanical properties achieved by adopting various measures to replace the material with natural coarse aggregates (NCA). Some of the ways include limiting the replacement of recycled concrete aggregates (RCA) to less than 30%

of the volume of the coarse aggregate, pre-soaking the material before mixing, introducing a two-stage mixing approach to cater for the higher water absorption property of RCA, the use of mineral additives as well as the use of water reducing superplasticizers (Evangelista & de Brito, 2010; Silva et al., 2015; Dimitriou, Savva & Petrou, 2018; Rajhans et al., 2019). A further discussion of these methods is highlighted in section 2.8.4 of this chapter.

Even though much research has been done on recycled concrete coarse aggregates (RCCA), minimal research has been conducted on recycled fine aggregates (RFA). Specifically, research on the durability qualities of concrete mixes with RFA partial inclusion (Oikonomou, 2005; Evangelista & de Brito, 2010; McNeil & Kang, 2013; Guo et al., 2018). As a consequence of the limited research on RFA, there is a lack of policies and quality control guidelines in the recycling industry that illustrate a standard way concrete stakeholders can adopt in the management of C&DW (Fathifazl et al., 2009). And although studies such as those of Evangelista & de Brito (2010) have shown that 30% substitution of natural fine aggregates (NFA) with recycled fine aggregates for structural concrete production is practical, the lack of standards and codes presents a challenge to the use of recycled concrete aggregates in the construction industry.

The use of recycled concrete aggregates, whether partially or fully replaced in the construction industry, has been reported to have varying results depending on the quality and source of the original concrete. As a result, it is generally concluded that recycled concrete aggregates have reduced performance properties with respect to their natural aggregate concrete. Similarly, the larger the replacement level of recycled aggregates, the lower its overall properties (Radonjanin et al., 2013). Different categories on the use of recycled aggregates have been published through the Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de et ouvrages (RILEM) Committee to limit their applications in concrete use, see *Table 2-3* (RILEM TC 121-DRG, 1994). In grade M25 and lower reinforced concrete structures, the Indian Standard IS: 383 allows up to 20% recycled concrete aggregates to replace the coarse fraction in concrete mixes.

Regardless of these reported inferior characteristics of recycled concrete aggregates, the coarser fraction of about 19 mm to 4.75 mm size fraction has been investigated as a potential alternative up to the 25% replacement level of RCA (Etxeberria, Marí & Vázquez, 2007; Kou & Poon, 2012; Duan & Poon, 2014; Thomas, Thaickavil & Wilson, 2018; Pacheco et al., 2019). The compressive strength of concrete made with recycled coarse aggregates up to 30% can be compared to compressive strength made with natural aggregate. (Tam & Tam, 2007; Behera et al., 2014). RILEM specifications on recycled coarse aggregates are based on assumptions that the recycled material is greater than or equal to 4 mm in size for concrete production, and some researchers have accepted the use of these materials up to the extent of 30% and less for structural purposes (RILEM TC 121-DRG, 1994; Etxeberria, Marí & Vázquez, 2007; Zega & Di Maio, 2011; Xiao, Lu & Ying, 2013; Xuan, Zhan & Poon, 2017). Kazemian, Rooholamini & Hassani (2019) summarises that various and contradictory results with respect to compressive and flexural strength of concrete containing recycled concrete aggregates are conclusively due to the variability in original concrete, crushing process, concrete mix design and water-to-cement ratio.

This research focuses on replacing recycled fine aggregates (RFA) with a standard size of 4.75 mm and below since the use of RCCA has been reported extensively. Some research discards the use of RFA due to their absorption capacity, which can lead to higher shrinkage and a porous cement paste (Etxeberria, Marí & Vázquez, 2007). However, this research investigates the presence of a porous cement paste as a basis for a secondary reaction that may lead to better durability properties of the concrete mix.

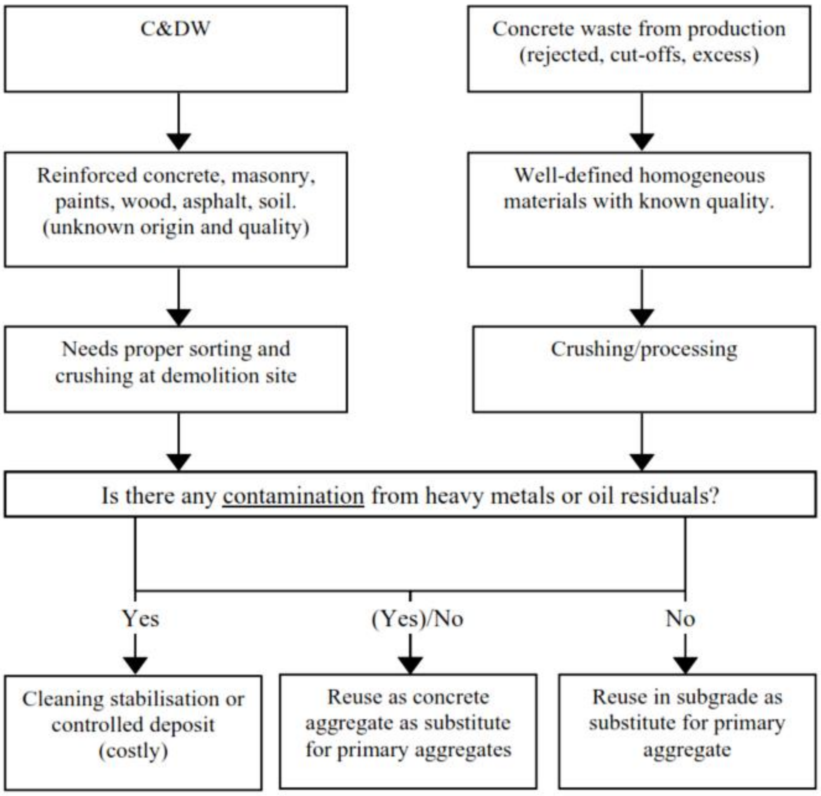


Figure 2-4: Treatment procedure for recycled concrete aggregate (ECO-SERVE, 2004)

2.5.3 Challenges associated with the use of C&DW as aggregate in concrete

The challenges associated with the use of construction and demolition wastes can be described in two methods: the overall adoption of C&DW as an alternative resource in the construction industry and the quality or performance of the resource as a construction material by engineering standards. Some of the challenges associated with the use of recycled fine aggregates in construction, as summarised by (Nedeljković et al., 2021), are as follows.

Variability

- Variability originates from the material source, both physical and chemical properties resulting in a wide range of mechanical and durability effects on the concrete.

Quality control

- Quality control of recycled aggregates is done during the demolition and sorting stage. The further control measures applied, the higher the quality achieved. Hence, when compared to natural aggregates, removing mortar from RFA particles and cleaning the material of contaminated substances would be more economical and environmentally expensive.

Standards and specifications

- Recently, the demand for the use of recycled aggregates in new concrete structures has been increasing. This demand requires firmer quality control measures for recycled aggregates than natural fine ones. However, the lack of well-developed guidelines for the quality control of recycled aggregates prevents its more comprehensive utilization in new concrete.

Research vs actual construction

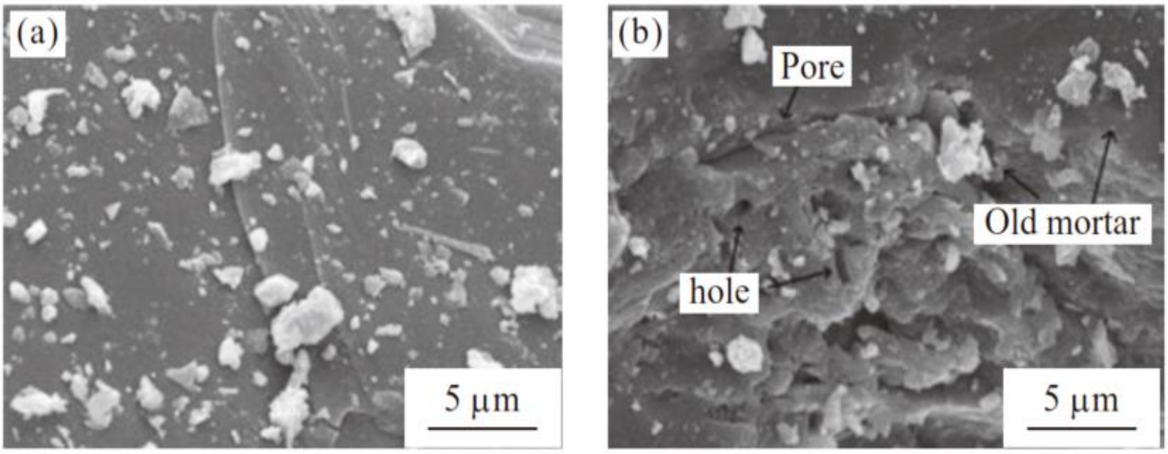
- Research work in the laboratory on the quality control of recycled aggregates is more demanding and thorough than in practical uses. There are three main concerns for practical applications of recycled aggregates in concrete: the source of recycled aggregates, upscaling the resource, and lack of codes and standards for investigation.

Furthermore, the lack of adoption in the public sector caused by lack of building specification, fewer sorting and diversion areas at the municipality level and incentives for waste management in adopting the material as an alternative resource in the community contribute to those challenges (GreenCape, 2020). Some scholars have reported several potential socio-economic benefits associated with using the resource on the quality or performance of the resource as a construction material. As well as some difficulties that originated from working with the material, we are still raising concerns about incorporating it in the new concrete application (Silva et al., 2015; Guo et al., 2018; Meddah, Al-Harthy & Ismail, 2020).

The RILEM specification for recycled aggregates deals with the coarse fraction of the material. It assumes that the only fraction that meets the standard specification is the coarse fraction. According to their classification based on the source of the material, environmental exposure and strength class of the concrete, their field of application and testing requirements is outlined. Subsequently, the Eurocode 2 on the Design of Concrete Structures are based on RILEM specifications, and eventually, the adopted values are in relation to the specified recycled aggregates classes (RILEM TC 121-DRG, 1994).

Numerous research concludes that the recycled coarse aggregates can only be as good as the parent material, and this poses essential questions about their overall performance in new construction (Thomas, Thaickavil & Wilson, 2018). Technically, RCA contains residual adhered mortar on its surface, as is shown in the microscopic image in Figure 2-5, illustrating the difference between NA and RCA viewed at 5µm in size. The double interfacial transmission zones cause the material to be more porous, have a higher water absorption (coefficient value between 4% - 12%), and lower density (between 2.1 – 2.4 g/cm^3) as compared to natural aggregates of similar volume (McNeil & Kang, 2013; Shi et al., 2016).

Hence, in order to design the appropriate concrete mix, it is crucial to determine material characteristics of each source. For instance, (1998) summarised that recycled fine aggregates have higher water absorption properties. Therefore, this informs the calculations for an adequate concrete mix design incorporating recycled concrete aggregates.



a.) Natural aggregates at 5µm b.) Recycled aggregates at 5µm

Figure 2-5: Microscope illustration of a) Natural fine aggregates b) Recycled fine aggregates (Zhu et al., 2018) under a microscope captured at 5µm

2.5.4 Various treatment methods adopted for the use of recycled concrete aggregates

In order to enhance both mechanical and durability properties of recycled concrete aggregates, various methods of modifying the original state of the aggregates have been investigated. A large amount of work has been practised on removing/modifying the adhered mortar on the material due to its reported high contribution to the lower properties of the materials (Malešev, Radonjanin & Marinković, 2010). The removal of adhered mortar is done through various techniques such as mechanical grinding or pre-soaking the material before mixing in acid solution (Liang et al., 2019), a two-stage mixing approach (Tam & Tam, 2007), additional mixing water, carbon dioxide treatment, additional superplasticizers, heat treatment and mineral additives.

These techniques have been adopted to produce more durable concrete when recycled concrete aggregates are utilised. These techniques have been reported to improve the durability properties of concrete made with recycled concrete aggregates (Matias et al., 2013; Guo et al., 2018).

As for the two-stage mixing approach, (Tam & Tam, 2007) illustrated the difference between the standard mixing method and the two-stage mixing approach, as shown in Figure 2-6.

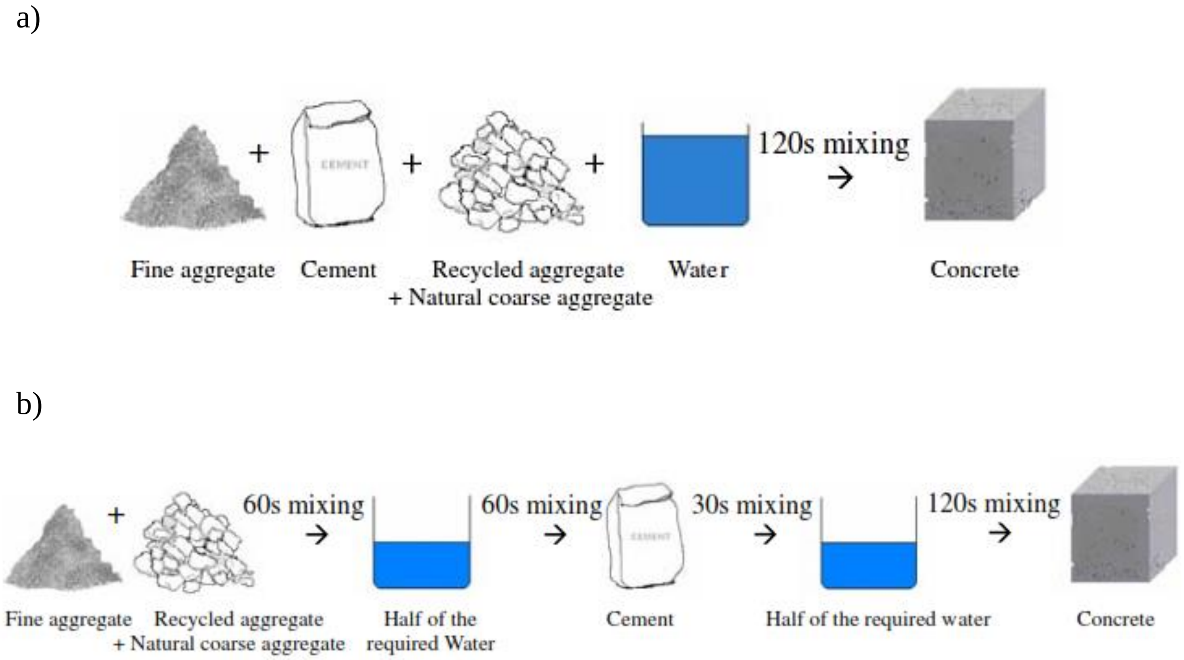


Figure 2-6:a) The standard mixing method b) the two-stage mixing approach by (Tam & Tam, 2007)

Primary and secondary crushing of the material has also been reported to improve the properties of recycled concrete aggregates. For instance, mechanically crushing of recycled concrete aggregates scientifically improves its morphology (Tam & Tam, 2007). Due to some of the weaker mortar being attached to the surface of the RCA, the optimal size distribution and morphology are produced when the materials are crushed using first a jaw crusher and then a rotary crusher to reduce the amount of adhered mortar. Furthermore, two-stage crushing decreases the effect on fresh properties of concrete, such as workability, caused by the presence of adhered mortar on the surface of recycled concrete aggregates (Matias et al., 2013).

A study by Ferreira, De Brito & Barra (2011) investigated the effect of mechanical and durability properties of different methods of water compensation and pre-saturation of the aggregates. In the study, Ferreira, De Brito & Barra (2011) found that pre-saturation adversely influences recycled aggregate concrete's mechanical performance and durability. Their investigation concluded that pre-soaking of the material creates extra water, which is absorbed into the attached mortar. And hence, the study concluded that a more practical technique would be to add extra mixing water to compensate for the water absorption.

Another reported technique in improving the use of recycled concrete aggregates is the pre-carbonation of the material. Pre-carbonation of the material aids in densifying the material and lessens the permeability of aggressive ions. Xuan, Zhan & Poon (2017) report that the inclusion of carbonated recycled concrete aggregates decreased the concrete's water absorption and permeability. For instance, replacing 100 per cent of carbonated recycled concrete aggregates improved the resistance by 15.1%, 36.4%, and 42.4% for bulk electrical conductivity, chloride ion permeability, and gas permeability, respectively.

Carbonation treatment has been reported to modify the morphologies of recycled aggregates, as illustrated in Figure 2-7 (Xuan, Zhan & Poon, 2017). The figure further shows that carbonation treatment aids the conversion of cement hydration products such as calcium hydroxide, calcium silicate hydrate, and ettringite to calcium carbonate crystals. These fibre-like products fill the bigger pores and densify the microstructure.

In addition, the use of mineral additives has also been vastly reported as one of the methods to adopt in the use of recycled concrete aggregates. The use of mineral additives helps reduce porosity, densify the microstructure of the concrete and improve strength. A similar case to the use of RCA has been reported in various research. Dodds et al. (2016) investigated the impact of using coarse RCA in conjunction with supplementary cementitious materials (SCM) on the durability properties of concrete made with recycled aggregates. The research study utilized surface resistivity, sorptivity, and accelerated chloride penetration tests to investigate concrete's resistance to chloride penetration. The results showed that for concrete with RCA, the inclusion of 30% fly ash and 50% ground granulated blast slag increased surface resistivity and resistance to chloride penetration while decreasing water absorption, presumably caused by the RCA's higher water absorption properties up to a replacement value of 60% RCA.

Lastly, heat treatment is also considered one of the improvement techniques for using recycled concrete aggregates. This technique is conducted to remove the adhered paste, which research shows contributes to the inferior properties of the material. However, it has been inquired if the use of heat to halt any chemical reactions doesn't consequently alter the microstructure of the recycled concrete aggregates. It is important to note that none of these enhancement techniques was adopted in my research to thoroughly investigate the influence that recycled fine aggregates have on a concrete mix and provide a solution that is viable and accessible in the industry.

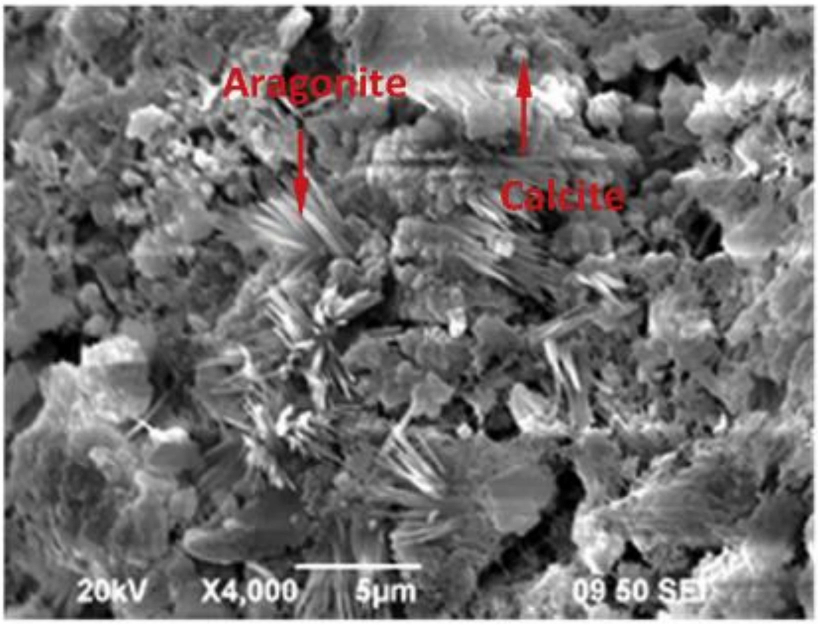


Figure 2-7: An illustration of the fibre-like cement products caused by pre-carbonation treatment of RCA (Xuan, Zhan & Poon, 2017)

Conclusively, due to the presence of hardened cement paste (mortar) on recycled concrete aggregates, there is a high significance to conducting material characterization on RCA compared to natural aggregates. Characteristics such as porosity and grading requirements and significant source fluctuations in quality control remain some of the biggest challenges in providing heterogeneity control of RCA. As mentioned earlier, the variability of RCA properties due to their different sources and handling procedures has been challenging. And therefore, aggregate properties play a crucial role in the behaviour of concrete mixes.

2.5.5 Demand in construction for recycled concrete aggregates

The demand for aggregates for construction has increased due to factors such as population increase, rapid urbanization that necessitates an increase in land infrastructure, residential, commercial, and recreational projects as well as industrial activities, and advancements in concrete technology. For instance, initially, deposits of natural aggregates were only found in the nearby localities in some locations. Still, recently, most deposits have been located on the outskirts of most cities, where large amounts can be produced and thus resulting in higher costs of transportation (Motsie & Malematja, 2014).

A global demand estimation of construction aggregates is reported to be more than 40 billion tons per annum (UNEP, 2014). Data from the Freedonia group estimates a rise of 2.3% per year to 47.5 billion metric tons of construction aggregates by 2023. In Europe alone, about 180 million tons or about 480kgs/person in a year of construction and demolition wastes were generated in 2004 (Fischer & Werge, 2009; Pacheco Torgal et al., 2011; Radonjanin et al., 2013). An estimate by the U.S. Department of Transportation (2004) predicted that about 2.5 billion tons per year of construction aggregates were to be used by 2020 in the united states alone.

Pacheco et al. (2019) summarises that about 48.3 million metric tons of construction aggregates were estimated by Eurostat in 2015. Additionally, the reuse of concrete in new construction practices will cater to aggregate consumption and waste generation challenges. The European Aggregates Association (UEPG) estimated that the demand and turnover of construction aggregates in Europe were about 3 billion tons and 15 to 29 billion euros a year, respectively, in 2017, an approximate difference of about 4 to 10 times (Meddah, Al-Harthy & Ismail, 2020). The 2nd edition of The Mineral Products Industry at a Glance – Key Facts of Britain summarises that crushed rock is the main constituent of aggregates supply. And about 28% of recycled and secondary aggregates are used – which is about 56 million tons of recycled aggregates used in construction in various sectors (MPA, 2014).

Various reports show that some parts of the world, including the pacific/Asia regions, have experienced sand resource depletion. Local and international news outlets have reported on the illegal mining of sand in countries such as Indonesia and India to cover the impact of these illegal activities on the neighbouring communities. An article from The Economist (2017) reports about $2.3 billion a year's worth of illicit market for natural sand and quantities of the global demand for construction sand, as illustrated in Figure 2-8.

Figure 2-8: An estimate graph of the global demand for construction sand from a market research firm, the Freedonia Group (TheEconomist, 2017)

Highley et al. (2019) summarised that in 1989 there was a peak in the consumption of sand and gravel of about 300 million tons, and 188 million tons in 2017. And one of the reasons that caused a decline in primary aggregates consumed per unit of new construction in Great Britain was the introduction of environmental taxation on landfills and aggregates production and the increase in the usage of alternative aggregates such as construction and demolition wastes.

In South Africa, Cole, Ngcofe & Halenyane (2014) summarised that a substantial amount of building sand was cleaned out during the development of places such as Khayelitsha and the greater Cape Town area, which predicted the exhaustion of construction sand resources in 20 years. The report also suggested that crusher sand from Table Mountain Group sandstone would be the most suitable replacement and agreed that transporting sand over long distances (above 80 km) would result in higher financial resources. The alternative of utilizing crusher sand along with dune sand has currently been adopted and is widely used in the western cape because of its sustainability long-term, as mentioned in Section 2.6.

It is evident that the demand for aggregates worldwide is increasing, leading to the investigation of alternative resources of aggregates. The use of recycled concrete aggregates is one of the ways to tackle this growing demand.

2.6 Properties of natural aggregates

The following sections illustrate the differences between natural and recycled concrete aggregates and review the properties of concrete made with natural and recycled concrete aggregates, emphasizing long-term durability properties in concrete with an emphasis on fine aggregates.

2.6.1 Particle shape and size

The particle shape of aggregates refers to the dimensions of aggregates such as length, width, and thickness and the angularity or smoothness and flakiness. The shape description can be estimated from sphericity, smoothness, and form. For instance, depending on the rock, form and efficiency of the crushing equipment, crushed aggregates may range from well-shaped cubic and sub-angular particles to strongly angular particles, flat and elongated, or flaky particles, as seen in Figure 2-9. On the other side, natural gravels appear more spherical because of the wear mechanism resulting in natural rounder edges (Alexander & Mindess, 2005).

Studies show that particle shape and size of aggregates influence the packing density and internal aggregate interlock in a concrete mix. These factors directly affect the plastic properties of concrete, i.e., concrete workability measured through different w/b ratios. The water requirement estimation can be used as an indirect measure of the particle shape (Graham Grieve, 2009). Fine aggregates affect the water requirement of concrete during mix design more than coarse aggregates. For instance, finer aggregate particles require more cement to achieve the required mix design. Consequently, the use of more cement adds to the cost inference in the concrete production at large due to its high-cost value among the other concrete constituents (Highley et al., 2019).

Furthermore, the source and extraction of aggregates affect their shape and size, which may also influence the hardened properties of concrete, such as concrete strength. Angular particles have a higher packing density and internal aggregate interlock, which improves the strength of concrete compared to flaky particles (Alexander & Mindess, 2005). Limitations on particle shape and size of aggregates used in concrete are summarised in the South African Standard SANS 1083 and British Standard BS 882. No limitations are described for both coarse and fine aggregates in the ASTM.

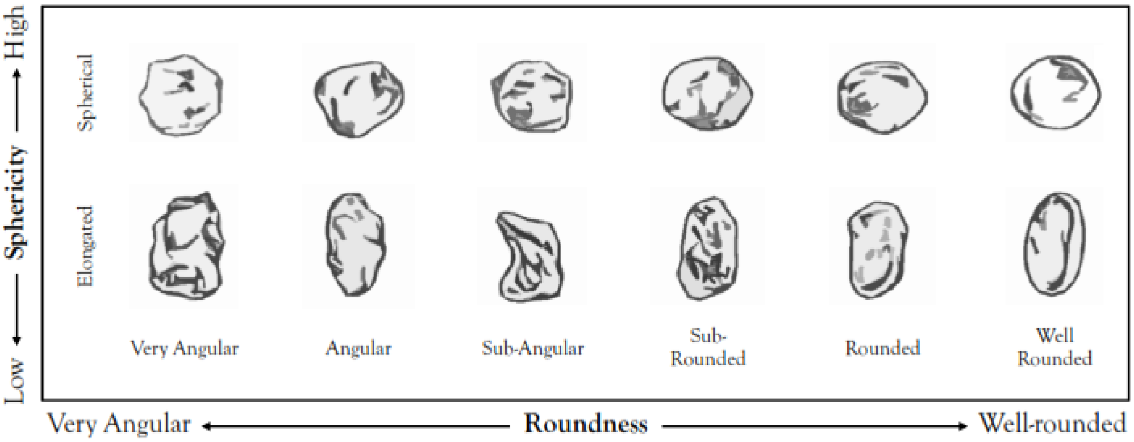


Figure 2-9: Physical features and their classification based on their morphology (Alexander & Mindess, 2005)

2.6.2 Gradation (particle size distribution)

Gradation is the distribution of standard-size aggregates that depict concretes nature as a bound system. This physical property controls the workability and other fresh properties of concrete, inclusive of cohesiveness and bleeding. Alexander & Mindess (2005) states that a well-graded combination of aggregates provides mixes that can be easily hauled, placed and compacted.

There are various types of grading for aggregates; however, uniform and continuous grading are the most commonly described. Uniform grading generates a significant amount of voids between the particles, while continuous grading decreases the void space and reduces the specifications for paste required due to the wide availability of particle sizes that can interlock continuously. Aggregate distribution governs the number of voids to be filled and the surface area of the aggregates that need to be coated with the concrete paste. It is also essential to include the size of the maximum aggregate possible in a mix since it decreases the surface area per unit volume of the aggregates, which the paste must cover, hence, lowering the amount of water required in the mix.

A grading curve is a graphical representation of an analysis of a sieve and represents aggregate particle size distribution. Under typical standard requirements, two grading curves, a lower and upper limit curve, represent what is known as a grading envelope. Aggregates will typically be required to fall under the grading envelope in order to be used for concrete production (Alexander & Mindess, 2005).

A typical gradation curve and procedure for performing gradation analysis of aggregates is summarised in the SANS 201 and ASTM C33. Such numerical grading and particle size characterization calculations can optimize grading, design acceptable aggregate blends, and satisfy specifications. For instance, in South Africa, blending two different aggregates is done to produce a standard specification of aggregates through optimized gradation.

2.6.3 Porosity and water absorption

Porosity is the ratio between the internal pore volume to the overall volume of the solid part. This property in aggregates influences the absorption and particle relative density of the concrete which is indirectly related to concrete stiffness, compressive strength, permeability and durability against aggressive environments (Graham Grieve, 2009). In determining the absorption of aggregates, the porosity of aggregates in the laboratory is determined by allowing water to seep into oven-dried aggregates under submersion and then measuring their mass in the saturated surface dry state.

Aggregate absorption is highly influenced by its porosity. A more porous aggregate will absorb more water than a less porous aggregate. Naturally, aggregates consist of some per cent of internal pores or voids, but for water absorption to occur, pores should be interconnected and open to the surface. Consequently, only permeable pores can be used to measure porosity in the laboratory (Alexander & Mindess, 2005; Graham Grieve, 2009).

Under standard laboratory conditions, absorption is achieved by allowing water to seep into oven-dried aggregates while submerged and then measuring their mass in the saturated surface dry state. Absorption is then calculated as the percentage ratio of the rise in the mass of the oven-dried sample after saturation to the mass of the saturated surface dry sample. Water absorption calculation of concrete aggregates is stipulated in the SANS 5843.

2.7 Properties of recycled concrete aggregates

A brief review of the properties of recycled concrete aggregates is discussed in this section. Some of these properties form a basis for investigating the objectives of this research. In summary, investigating the influence of replacing NFA with RFA and assessing if the new concrete has similar durability properties compared to natural aggregates. The quality of recycled concrete aggregates is affected by various factors that may significantly impact the performance of intended concrete. Vasco et al. (2015); and Wang et al. (2019) summarise these factors as size, type, source and the beneficiation methods used. Tam & Tam (2007) reports that because recycled concrete aggregates are made from construction and demolition waste, it has a lower density, increased water absorption, and porosity due to being subjected to years of performance and service. These properties restrict RCA to lower-grade concrete applications owing to the adhered cement past attached to its surface.

The following section discusses particle size and gradation, relative density, and water absorption of recycled concrete aggregates.

2.7.1 Particle shape, size and gradation of RCA

The particle shape of recycled concrete aggregates is dependent on the crushing process. (Sagoe-Crentsil, Brown & Taylor, 2001) found that RCA produced in the plant had smoother and round particles, which influenced better workability of the concrete. Technically, the amount of adhered cement on the RCA surface is influenced by the crushing process, size, shape and dimension of the RCA origin (Paul, 2011). Figure 2-10 illustrates the relationship between the properties of aggregates, such as porosity and size and concrete performance in the fresh and hardened state.

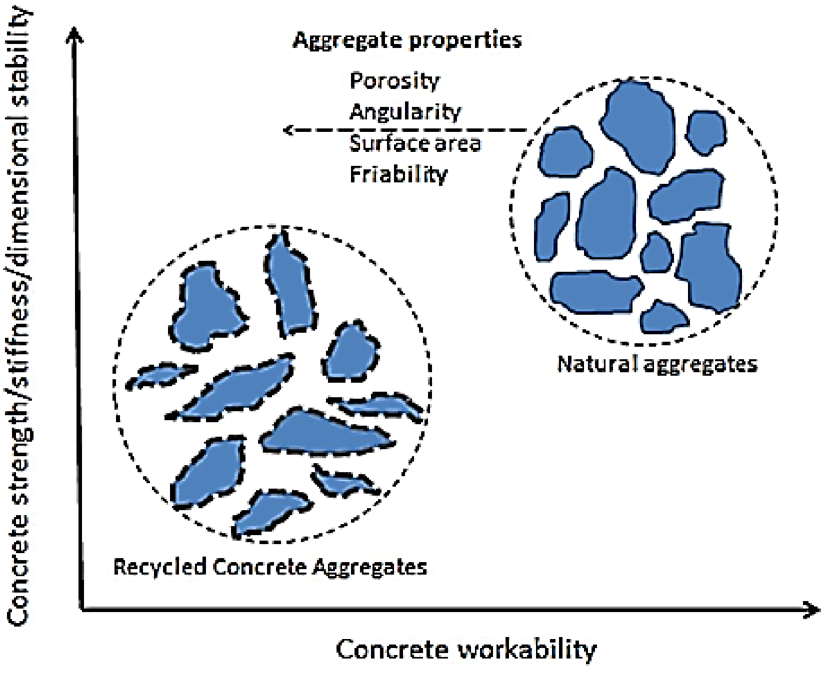


Figure 2-10: Relationship between aggregates properties and concrete performance between natural and recycled concrete aggregates as illustrated by (James Mackechnie & Munn, 2011)

A fact sheet by (Highley et al., 2019) summarises that finer aggregate sizes require more cement in the mix design, which ultimately has a cost implication in concrete production since cement is the most expensive of the constituents of concrete. The increased surface area of sand particles contributes to the increased demand for cement. Additionally, this increases the possibility of physical-chemical interactions between the cement paste and the aggregates particles, which will somewhat decrease the actual water binder ratio. And hence it is essential to optimally specify the properties of aggregates such as particle size, distribution, and shape because they influence the mix design proportions and overall performance in general.

Compared to NFA, RCA has been reported to have a rounder and a spherical shape due to its production process, influencing the good flowability of concrete during the mix design (Sagoe-Crentsil, Brown & Taylor, 2001; Shayan & Xu, 2003). The presence of the adhered mortar helps smoothen the rougher edges on the original aggregates, allowing the new cement paste to flow easily around the aggregates.

In summary, these characteristics are the main factors limiting the use of RCA in concrete applications (Etxeberria et al., 2007).

2.7.2 Porosity and water absorption of RCA

Similarly to the relative density, various researchers have reported that the presence of adhered mortar on RCA increases porosity, which allows the aggregates to hold more water than natural aggregates (Ravindrarajah, Stewart & Greco, 2001; Etxeberria, 2004; Eguchi et al., 2007; Tam & Tam, 2007; James Mackechnie & Munn, 2011; Kim et al., 2019). Ravindrarajah, Stewart & Greco (2001) concluded that the average water absorption value in recycled concrete aggregate was approximately seven times higher than in raw aggregates from a batch of 15 samples. The quantity and quality of the adhered mortar influence the absorption capacity of recycled aggregates.

Furthermore, the porosity of natural aggregates is purely influenced by the type of aggregates themselves (Limbachiya, Leelawat & Dhir, 2000; Sagoe-Crentsil, Brown & Taylor, 2001). The water absorption capacity of recycled aggregates is directly influenced by the amount of residual adhered mortar found on the surface of the aggregates. Research by Etxeberria (2004) illustrates that the smaller the size of RCA, the higher the amount of residual mortar as a percent of the weight of cement paste attached to the original aggregate. The correlation between water absorption values of RCA and density values is summarised in Figure 2-11.

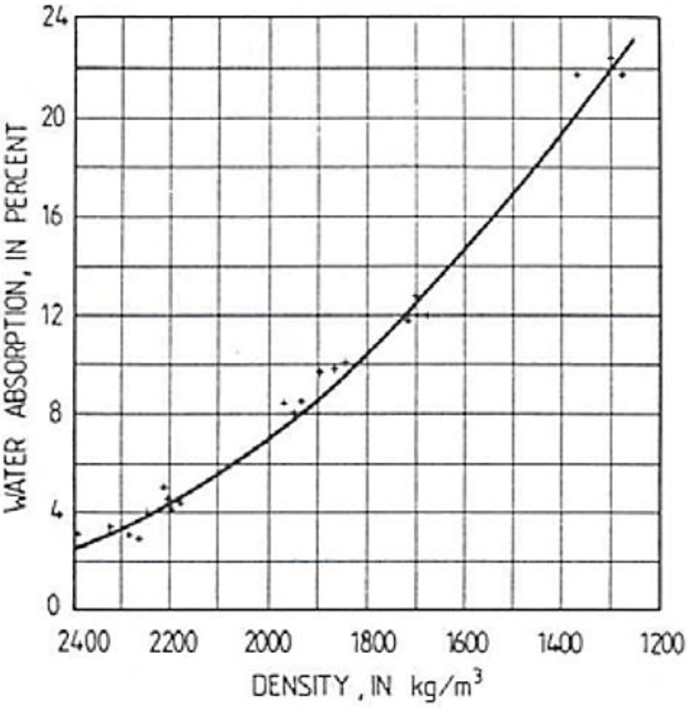


Figure 2-11: A correlation of water absorption and density of the recycled concrete aggregates by kreijger 1983 (Etxeberria, 2004)

RCA's higher water absorption and porosity are due to the adhered residual mortar on the underlying rock, allowing the recycled aggregates to hold more water in their pores than natural aggregates (McNeil & Kang, 2013). Research by (Shayan & Xu, 2003) found a difference of 4.2% in water absorption values of RCA compared to natural aggregates in their saturated surface dry conditions. These characteristics contribute to less density, higher porosity, and, hence, lower mechanical properties when mixed in concrete (McNeil & Kang, 2013; Thomas et al., 2019).

The use of recycled concrete aggregates has been permitted in IS:383 for less than 10% water absorption, along with prewetting to saturate the aggregates before batching and mixing. The use of RCA for structural applications is limited to an absorption capacity of 5%, characterised by both porosity and water absorption of the aggregates. It was also reported by Etxeberria (2004) that due to the high absorption capacity of recycled concrete aggregates, a maximum of 20% of recycled aggregates was specified to be used in concrete. RILEM publication on recycled aggregates categorises them into three types according to their absorption level and dry density, as seen in Table 2-3.

Table 2-3: Acceptance criteria for water absorption when using recycled concrete aggregates as adopted from (McNeil & Kang, 2013)

RILEM 1994			
Recycled aggregates type	**Type 1 – Masonry rubble**	**Type 2 – concrete rubble**	**Type 3 – mix of (min 80%) NA and (max 20%) RCA**
Oven dry density criterion (kg/m^3)	≥ 1500	≥ 2000	≥ 2500
Absorption level of aggregates criterion (%)	≤ 20	≤ 10	≤ 3

2.7.3 Relative density of RCA

The amount of adhered mortar on the surface of recycled concrete aggregates influences its relative density. Studies by (Etxeberria, 2004; de Juan & Gutiérrez, 2009; Debieb et al., 2010; McNeil & Kang, 2013) illustrate the higher amount of adhered mortar on the surface of the recycled aggregates, the lower it is relative density. The adhered mortar on the aggregate is lighter than the rock compared to the natural aggregate of the same volume in the saturated surface dry state, which decreases the density of the RCA (Limbachiya, Leelawat & Dhir, 2000; Sagoe-Crentsil, Brown & Taylor, 2001). It should be noted that a correlation exists between water absorption and the density of the recycled aggregates, as illustrated in Figure 2-11. Similarly, it is reported by Çakir (2014) that an inverse relationship is observed between density and water absorption ratio and that the relative density progressively decreases in concrete with a higher amount of RCA replacement.

Etxeberria, (2004) also explains that the density of recycled concrete aggregates is dependent on the strength of the original concrete and the size of the aggregates. Recycled concrete aggregates have been reported to have a 7% to 9% lower relative density due to the amount of adhered mortar on the surface of the stone (Limbachiya, Leelawat & Dhir, 2000; Malešev, Radonjanin & Marinković, 2010). (Sagoe-Crentsil, Brown & Taylor, 2001) reported a 17% difference between RCA and NA in their bulk densities of 2,394 and 2,890 kg/m^{3,} respectively.

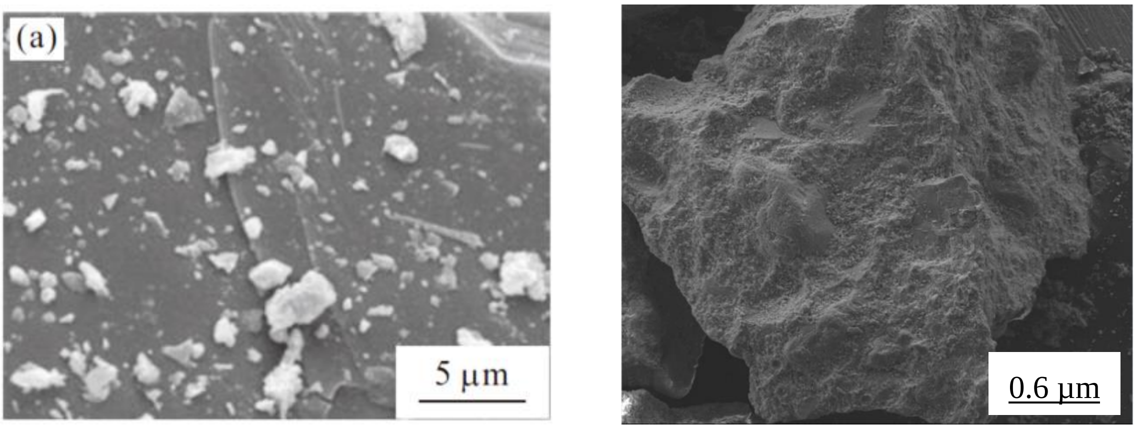
In summary, the key takeaway is that the qualities of RCA are precisely the same as those of natural aggregates; the only difference is that the values of the individual parameters will vary, which will affect the concrete.

2.7.4 Adhered cement paste on the surface of RCA

The major distinction between conventional concrete aggregates and recycled concrete aggregates is the adhered cement paste found on the latter's surface. The adhered cement paste referred to in this research work is the cement paste found on the surface of recycled concrete aggregates. This attached cement paste on the original aggregates contributes to the reported lower relative density, lower compressive strength, and higher water absorption capacity than concrete made with natural aggregates (Tam, Soomro & Evangelista, 2018). A microscopic illustration of the adhered cement paste on the surface of recycled aggregate is seen in Figure 2-12. Figure 2-12 shows a comparison between the surface of a natural aggregate and recycled aggregates captured at 5 µm in size.

Pepe et al. (2014) and Pepe (2015) reported that recycled concrete aggregates are multi-phased materials compared to the three-phased conventional concrete material. The former concrete consists of two interfaces, the interface between adhered mortar and the original aggregate and the new interfacial transition zone between the new mortar and the recycled aggregate. The latter concrete consists of a mortar matrix, aggregates and one interfacial transition zone between the paste and the aggregate. As inferred in the earlier properties, the reduced concrete performance of concrete made with recycled concrete aggregates is attributed to the adhered mortar, as seen in Figure 2-13. Therefore, as the adhered mortar increases, water absorption properties also increase, and the fresh concrete's workability decreases (Seo & Choi, 2014).

Analysis by Etxeberria et al. (2007) indicated that the volume of RCA adhesive mortar depends on the grinding process and the water/cement ratio of the original concrete. The fraction of mortar adhered to the RCA surface can be minimized by grinding the RCA to a scale similar to that of the conventional aggregates in the source of concrete (Akbarnezhad et al., 2013). Akbarnezhad et al. (2013) also report that the properties of concrete containing RCA depend primarily on the mortar quality of RCA, which consequently depends on the strength of the original concrete or source of the material. The essential factors that determine the properties of concrete are the original concrete characteristics, the recycling process and the size fraction of aggregates (González-Taboada et al., 2016).



a.) Natural aggregates at size 5µm b.) Recycled aggregates at size 0.6 µm

Figure 2-12: Microscope illustration of a) Natural fine aggregates at size 5 µm b) Recycled fine aggregates at size 0.6 µm (Zhu et al., 2018) under a microscope captured at 5µm.

On the other hand, some have investigated the possibilities of using this large percentage of adhered mortar to their advantage and suggested various ways. The reactivity caused by adhered mortar on the finer fraction of RCA could be replaced with supplementary cementitious material as a way to optimize their properties and provide an eco-efficient cement-based concrete. Furthermore, studies have investigated the use of RFA as a mineral addition to cementitious materials and raw materials in the cement production process (Oksri-Nelfia et al., 2016; Diliberto et al., 2017).

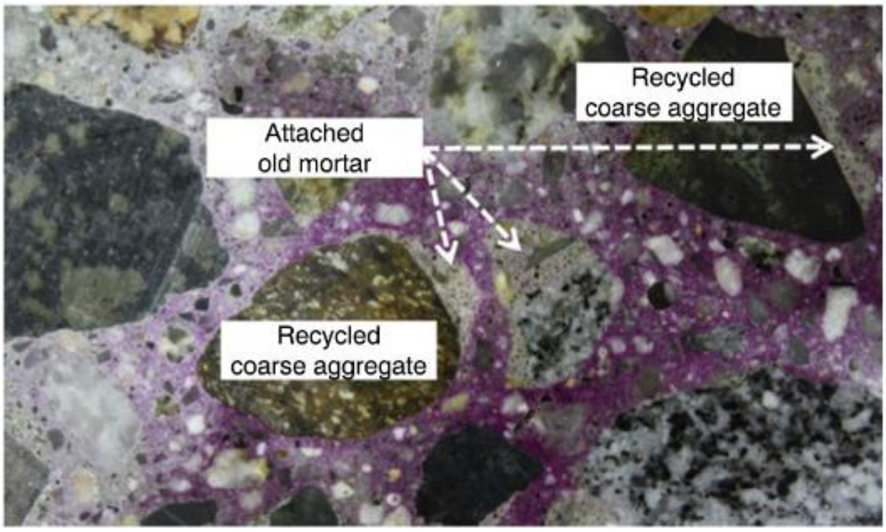


Figure 2-13: An illustration of the recycled concrete aggregate interface under microscopic investigation by (Seo & Choi, 2014)

In this research, the same possibility is investigated through the non-modification of the material during the mix design process and examining the influence of partial replacement of NFA with RFA on the durability properties of concrete. Since the surface of recycled fine aggregate contains an adhered mortar that is originally from the parent concrete, it is correlated that the existence of this layer influences the properties of this material. Due to the cement attached to aggregates, the water absorbed during the mixing process likely influences self-cementation through the continuous hydration of cement. This research looks into the probability of this secondary reaction in concrete made with recycled concrete and its effect on durability properties. This influence will be tested through the short-term durability index tests and long-term durability tests such as the bulk diffusion and carbonation test.

2.8 Properties of concrete made with natural and recycled concrete aggregates

The use of concrete to build structures has been recorded since early Roman times. Buildings in Rome, such as the pantheon, illustrate the evidence of concrete’s durability properties to date (Schiessl, 1996). In the past, structural designers used mechanical properties such as strength and stiffness to specify durability properties. In the boom of this technology, a lot of research and development work aimed to optimise the strength or load design factors in making economic structures. As a result, durability measures have been widely investigated and clarified according to structural performance. This approach later on raised durability issues concerning the environment and workmanship on site that caused concrete deterioration and failures within the design life of many structures. All reactions that may cause deterioration in conventional concrete require the transportation of substances from outside to inside the concrete matrix or vice versa. Hence, it is essential to understand the transport mechanisms of concrete in order to deal with concrete deterioration.

2.8.1 Transport mechanisms of concrete

The penetration of aggressive ions primarily influences concrete deterioration within the concrete pore structure. All reactions between compounds inside the concrete require moisture from outside the concrete environment (Claisse, 2020). Therefore, grasping the transportation pathways in concrete made with recycled concrete aggregates is equally crucial. The processes that enable moisture, carbon dioxide gas, chloride ions, oxygen, sulfate ions, and electrical current to pass through reinforced concrete govern the phenomena that cause it to degrade. This phenomenon is known as penetrability. Penetrability is defined as the degree to which the concrete allows gaseous, liquid or aggressive ions into its pore matrix (Ballim, Alexander & Beushausen, 2009).

Transport mechanisms and the influence of interfacial transmission zone affect the concrete durability properties. The transport mechanisms of ionic species are permeation, diffusion, sorptivity, convection and migration. The transport properties of concrete through the concrete pore matrix due to permeation, diffusion, sorptivity, convection, and migration govern the deterioration process of concrete (Bertolini et al., 2004). The rate at which these mechanisms occur depends on the concrete's environment, interaction with the pore system, and the reaction of infiltrated substances with some of the concrete’s components (Schiessl, 1996).

Permeation is defined as the process of fluid movement through the concrete pore structure by an external pressure while the fluid fully saturates the concrete. This process is indicated during carbonation testing through the Oxygen Permeability Index test. Sorptivity is the movement of a wetting front through the concrete pores by capillary forces. The degree of pore interconnection, presence of curing agents on the surface of the concrete, compaction, aggregates distribution and the concrete mix composition influence sorptivity. During the durability index testing, it is calculated through the water sorptivity index test. Diffusion is the movement of dissolved ions from a region of high concentration to a low concentration. This process is illustrated during the bulk diffusion test in the laboratory. Convection is the movement of solutes such as chloride and sulphate ions due to the bulk movement of water in concrete. Migration is the movement of ions in a solution under an electric current. This process is mostly used in laboratory experiments to accelerate the diffusion of chloride ions in the concrete sample (Nonwoovens, 2002). Migration of ions can be observed during the chloride conductivity index test.

The transport mechanism, concrete properties such as porosity and presence of microcracks, the binding of substances transported through the hydrated cement paste, as well as the surrounding environment of the concrete surface along with its changes over time govern the kinetics of transport in concrete as seen in Figure 2-14 (Bertolini et al., 2004). Primarily, the permeability of the hydrated cement paste, particularly at the interface of the aggregates particles, influences the overall permeability of concrete (Ballim, Alexander & Beushausen, 2009). Transport mechanisms provide a performance measure to the quality of the concrete cover due to the ease of penetration of ions or fluid from carbonation or chloride ingress processes into the concrete microstructure. Understanding these processes is crucial for fabricating control measurements or improving techniques for durability in conjunction with condition assessment, repair and rehabilitation of structures.

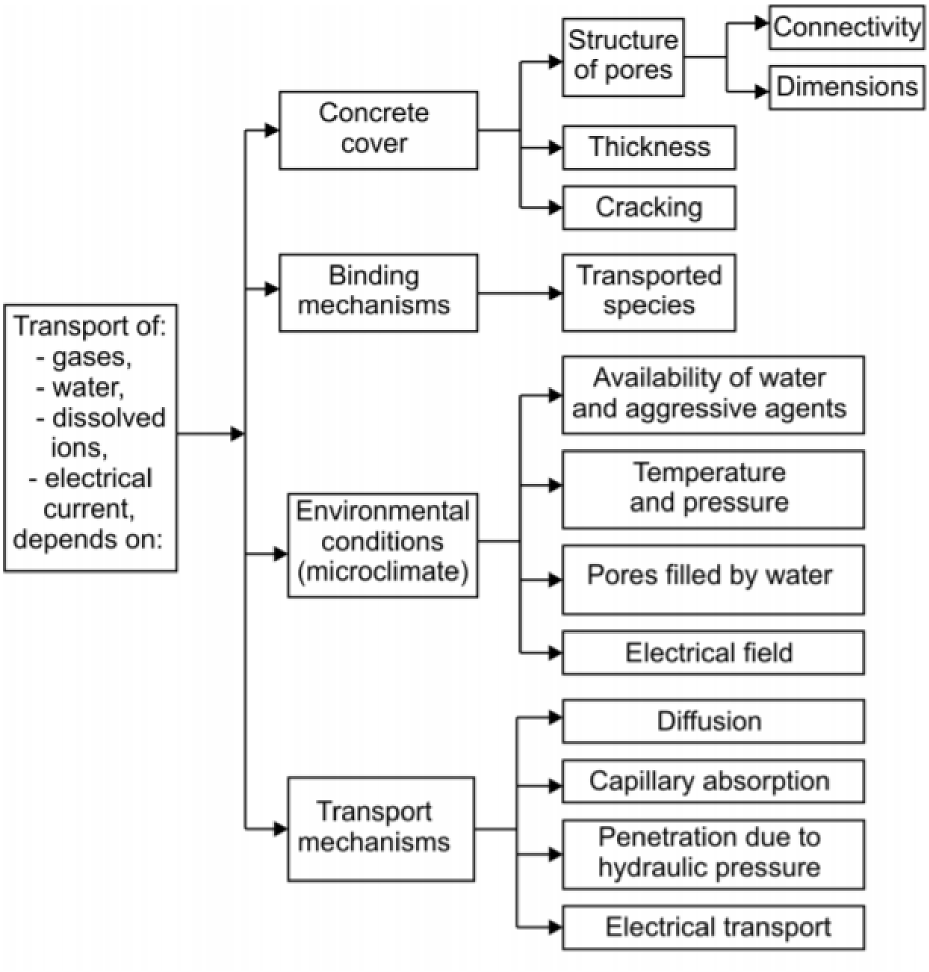


Figure 2-14: Basic agents controlling transport mechanisms in concrete by (Bertolini et al., 2004)

Since the durability of concrete is affected by the transportation mechanisms, Claisse (2020) summarises the factors that affect the durability of concrete, as seen in Figure 2-15.

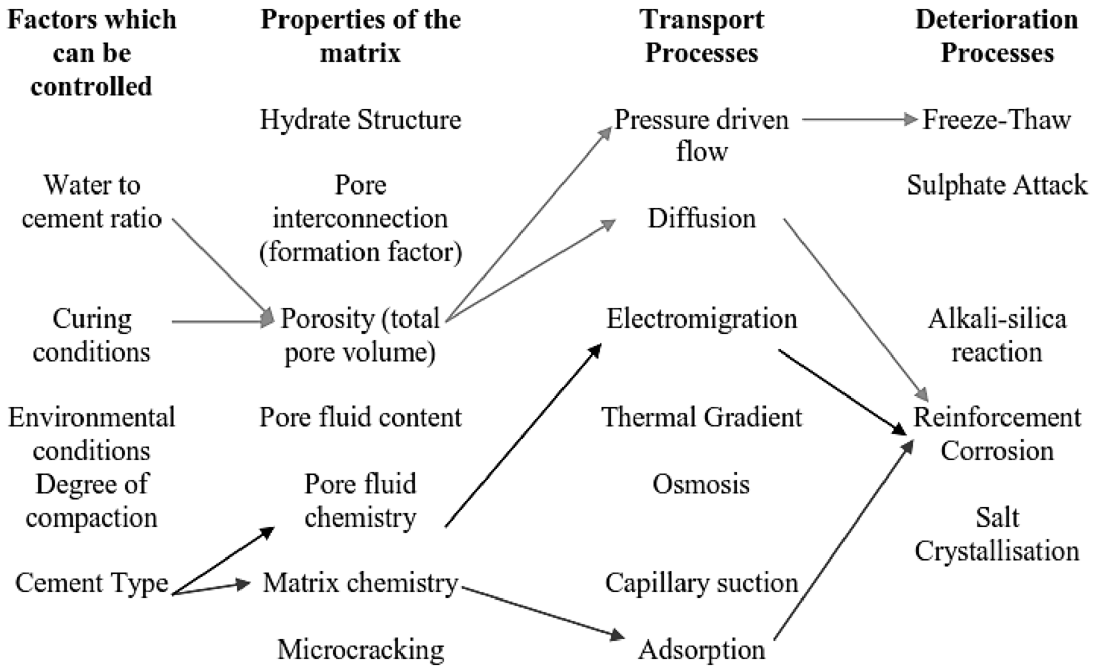


Figure 2-15:First column to the left summarises the factors that indirectly affect durability and can be controlled. The second column illustrates factors that directly affect the durability of a concrete structure. The third column describes a summary of the transport processes. The last column displays the deterioration mechanisms (Claisse, 2020).

As shown in Figure 2-15, the properties of the matrix under the second column directly affect the durability of concrete. These factors include cracks and fractures, the interaction, and the pore interconnection, which indicate the direct pathways present in the concrete pore structure. The most common concrete defects are summarised in T*a*ble 2-4 and their means of transportation as adopted from Fulton's Chapter 27 on Remedial actions (Beushausen & Alexander, 2009).

Table 2-4: Common defects in concrete, deterioration process and means of transportation (Beushausen & Alexander, 2009)

Defects	Source	Causes	Means of transport
Concrete system	Cracks	Mechanical	Natural processes and design factors
		Chemical	Design factors and environmental exposures, e.g., sewers
		Physical	Airborne, Splash/wet zones
Corrosion of the reinforcement	Uniform and pitting corrosion	Carbonation	Carbon dioxide from the atmosphere
		Corrosion agents	Splash or wet zones
		Stray Currents	Environmental exposure

Çakir (2014) reports that cracks and fractures contribute to the poorer performance of concrete with RAC, formed during the production and procession stage, thereby rendering the aggregate weaker and more prone to transportation processes such as permeation, diffusion, and fluid absorption. These pathways are crucial to understanding the hypothesis utilized to investigate this research's influence on durability properties. Figure 2-16 illustrates the corrosion reaction during chloride ions and carbon dioxide transportation within the concrete cover. Figure 2-17 illustrates these ions' movement through a concrete matrix.

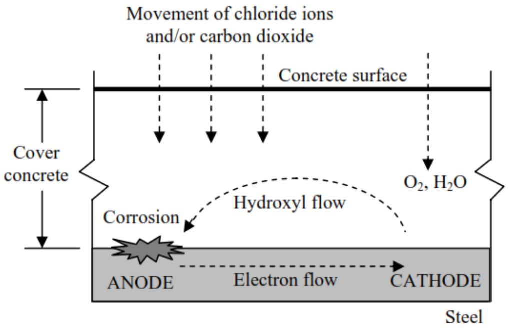


Figure 2-16: A schematic representation of transportation of aggressive ions into the concrete matrix (Alexander & Mackechnie, 2001)

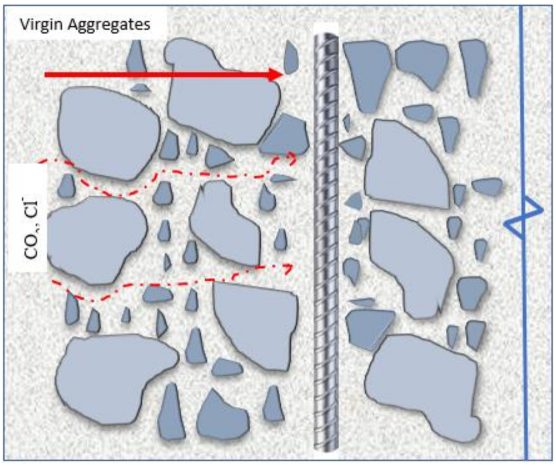


Figure 2-17: Transportation of aggressive ions in concrete made with virgin concrete aggregates

2.8.2 Compressive strength of concrete made with RCA

The compressive strength of concrete is the most indicative property to evaluate its performance of concrete. Most scholars have reported a negative influence of the recycled aggregate concrete quality, such as a reduction of the compressive strength, tensile strength due to the increased concrete porosity, water absorption, and a weak aggregate–cement paste interfacial bond (Buyle-Bodin & Hadjieva-Zaharieva, 2002). The heterogeneity in the source of recycled concrete aggregates influences its characteristics and overall properties.

The compressive strength of concrete made with RCA has been reported to be slightly lower than that of the conventional concrete because of the higher moisture content present on the surface dry state of recycled concrete aggregates, which forms a weaker mechanical bond between the cement paste and the aggregates (Poon et al., 2004). Hence, most reported work has adopted modification techniques to attain their desirable properties. For instance, using superplasticisers and extra water helps obtain more workable mixes.

Some of the compressive strength values from various authors are summarised in Table 2-5. Due to the lack of studies on RFA use without modification, all the studies summarised in Table 2-5 have adopted specific modification techniques in their mix design which contrasts with the methodology adopted for this study.

Table 2-5: A summary of compressive strength from various studies

Studies on RFA	Source of RFA	% Of RFA replacement	Modifications adopted	Compressive strength values at (28 days)
(Kumar, Gurram & Minocha, 2017)	C&D waste recycling plant of IL&FS Environmental Infrastructure & Services Ltd., New Delhi, India, where selective crushing of the C&D waste was carried out	0, 25, 50, 75 and 100	Two-stage crushing, the use of superplasticizers with a specific gravity of 1.05, and particles below 0.15 mm were removed.	40.72, 39.30, 37.40, 37.34 and 35.21 MPa respectively.
(Buyle-Bodin & Hadjieva-Zaharieva, 2002)	RMN company (Recyclage de Materiaux du Nord) located in Northern France, where the removal of impurities was adopted through a floating line	NAC1, NAC2, MAC, RAC1, RAC2, RAC3,	The use of superplasticizers, pre-soaking of the RA, and added water for workability purposes	**Water storage** 42.6. 54.8, 43.3, 31.4, and 39.4 MPa, respectively. **Air storage** 37.7, 47.7, 37.8, 29.5, 34.2, 38.1 MPa respectively.
(Zega & Di Maio, 2011)	Crushed concrete from different qualities and made with granitic stone	0, 20 and 30	Water reducing admixture was used	43.6, 42.7, and 41.4 MPa, respectively.
(Evangelista & de Brito, 2010)	Crushed concrete from the laboratory	0, 30 and 100	The use of superplasticizers, sealed RFA to prevent humidity transfer, and two different w/c ratios were utilized to adjust for	59.3, 57.3, and 54.8 MPa, respectively.

			the high-water absorption of RFA.	
(Pereira, Evangelista & De Brito, 2012)	Crushed concrete from the laboratory	0, 10, 30, 50, 100	The use of superplasticizers (SP1 and SP2)	Without superplasticizers (WS), Superplasticizer 1 (SP1) and Superplasticizer 2 (SP2) (0% RFA) - 39.5, 53.3, 65.2 MPa (10% RFA) - 40, 53.7, 64.6 MPa (30% RFA) - 38.6, 51, 65.4 MPa (50% RFA) - 37.6, 47.8, 63.2 MPa (100% RFA) - 38.6, 45.1, 63 MPa
(Pedro, de Brito & Evangelista, 2017)	Crushed concrete from the laboratory and crushed precast concrete of 73.2 MPa (28 days) and 74.5 MPa at an age greater than 28 days from the site.	0, 25, 50 and 100	The use of superplasticizers, effective water/cement ratio,	Reference concrete 72.6 MPa Site concrete 68.2, 66.5, 61.8 MPa Laboratory produced 68.9, 63.8, 61.0 MPa
(Kirthika & Singh, 2020)	Construction and demolition waste plant, New Delhi	0, 30, 50, 75, and 100	The use of superplasticizers, the triple mixing technique was utilized,	36.2, 36.8, 33.8, 31.7 and 30.1 MPa

A summary from (Yang, Chung & Ashraf, 2008) investigation's analysed that the lower compressive strength was attributed to the increased water absorption of the aggregates. Because of their higher absorption capacity, RA requires more water than regular concrete to achieve the same workability. The porosity in the constituents of concrete influences their compressive strength.

McNeil & Kang (2013) reports three factors that influence the compressive strength of concrete made with RCA. Equally to concrete made with natural aggregates, the w/b ratio mainly influences concrete with R CA. Also, the replacement level of RCA in the concrete mix and the amount of adhered mortar on the aggregates influence the attainment of compressive strength.

Up to 30% replacement of RCA, the compressive strength of the recycled aggregates concrete (RAC) gradually decreases as RCA increases. (Limbachiya, Leelawat & Dhir, 2000; Oikonomou, 2005; McNeil & Kang, 2013; Ozbakkaloglu, Gholampour & Xie, 2018; Thomas, Thaickavil & Wilson, 2018).

Limbachiya, Leelawat & Dhir (2000) concludes that no effect is observed on the strength of concrete, up to 30 % replacement level of recycled coarse aggregates, however, afterwards, the strength decreases as the RCA increases at testing ages of 7, 28, 60 and 90 days. It should be noted that an adjustment to the water/cement ratio was adopted to account for the effects of RCA on compressive strength. In addition, an experiment in Greece by Oikonomou (2005) showed that the use of RCA for a pilot structure is viable with the addition of only coarse aggregate (>4.75 mm) up to 30% replacement according to standard specifications.

Research by Thomas, Thaickavil & Wilson (2018) reports that the replacement ratio of recycled concrete aggregate plays an important role in the mechanical properties of concrete. Similar to most researchers, they summarise that the strength properties of concrete are not profoundly impacted when natural aggregates are replaced with up to 25% RCA. Furthermore, conclude that partial replacement of natural aggregates with RCA can be substituted in moderate exposure conditions as stipulated in the ASTM C1202. However, above 25 % replacement level of RCA, the mechanical properties are negatively influenced.

Recycled concrete aggregate performance is largely affected due to the residual cement paste on its surface. As a result, recycled aggregates concrete is less dense, more porous and has a higher water absorption capacity than natural aggregates concrete. According to McNeil & Kang (2013), replacing natural aggregates with RCA decreases the compressive strength, but even though RCA has been reported to have a negative influence on concrete properties, its application in large scale tests of whole structural members is a feasible alternative to adopt.

A study by Pereira, Evangelista & De Brito (2012) investigated the strength increase by using superplasticizers to carter for the reduced water-cement ratio as a result of using RCA. They found that the use of high-performance superplasticizers yielded concrete mixes with superior mechanical performance to those of natural aggregates with regular superplasticizers.

Ozbakkaloglu, Gholampour & Xie (2018) studied the influence of replacing natural aggregates with low contents of RCA of up to 25%. It was observed that the replacement of RCA up to 25% does produce concrete with similar mechanical and durability properties to those of natural aggregates with similar compressive strength. Similarly, Kumar, Gurram & Minocha (2017) investigated the effect of RFA as a substitute for natural aggregates at 0, 25, 50, 75 and 100% replacement levels by volume on the compressive strength of recycled aggregates concrete. It was observed that both fresh and hardened properties of recycled aggregates concrete had no significant influence with mixes up to 50% replacement level of RCA. Although, it was seen that compressive strength decreased by 13.51% at the 100% replacement level. Kumar, Gurram & Minocha (2017) concluded that the compressive strength of concrete made with RFA showed a decrease of 3.48% and 8.15% at a 25% and 50% replacement level. Their research modified the mixes, including superplasticisers and extra water content.

Nonetheless, high water absorption has been reported to contribute to higher compressive strength for concrete mixes with recycled aggregates at optimum replacement levels. Some scholars have concluded that the extra water absorbed by the adhered mortar seeps out after a duration of time and initiates a secondary hydration reaction of the un-hydrated cement in the concrete matrix and, in this way, yields higher compressive strength (Wickins, 2013).

It has been vastly reported that owing to the presence of old adhered mortar, recycled aggregates concrete has lower mechanical properties compared to natural aggregates concrete. Nevertheless, Kirthika & Singh (2020) concluded that the replacement of RFA at 30% illustrated an 11.0% enhancement in compressive strength than natural concrete at 56 days. Ferreira, De Brito & Barra (2011) concluded that high water binder ratios result in lower compressive mixes.

Corinaldesi & Moriconi (2009) studied the influence of mineral additions on 100% recycled aggregate concrete performance. They report an improved or similar compressive strength of concrete with recycled aggregate concrete by adding mineral additives to concrete without recycled aggregates. Çakir (2014) reports that at a 100% replacement level, the concrete compressive strength decreases about 24% after 28 days of curing. The compressive strength reduction is more pronounced above 50% of the replacement level. (Yang, Chung & Ashour, 2008) concluded that at a relatively lower RCA fraction, the concrete mix had an equivalent compressive strength value to the conventional concrete. The compressive strength values were 0.6 – 0.8 of the conventional concrete at higher RCA fractions. They also concluded that there was an improvement of compressive strength with age, at 56 and 91 days, illustrating that since at higher RCA fractions, there was the presence of more water stored in the pores, this water provided internal curing for the cement paste on the surface of the recycled aggregates. This absorbed water could be released into the new concrete mix and over time, enter the cement matrix to rehydrate the cement paste further and improve the concrete's strength. Furthermore, it is reported by (Ismail, Kwan & Ramli, 2017) that the effect of RCA's high-water absorption and the usage of a reasonably higher water binder ratio for RCA promotes water transfer during and after hydration. Matias et al. (2013) summarise that maintaining the aggregates gradation and the design of fresh concrete properties may lead to compressive strength values similar to conventional concrete.

Research by (Evangelista & de Brito, 2007) found that the compressive strength values of concrete with partial replacement of natural aggregates with recycled fine aggregates at 30% were similar to the values of conventional concrete for concrete with 60 MPa. It should be noted that these promising results were attributed to the presence of a large quantity of un-hydrated cement found on the surface of recycled fine aggregates. And due to their higher porosity, they form a stronger bond between the new and old cement paste.

In the next chapter on the experimental approach, although the mechanical properties are investigated, the main focus of this research is on the durability properties of concrete made with recycled fine aggregates. Both the influence on carbonation resistance and chloride penetration on concrete made with recycled concrete aggregates is discussed.

2.9 Durability properties of concrete made with natural and recycled concrete aggregates

The durability of concrete is mainly affected by its microstructure due to the influence of transportation of ions or fluids into the concrete's structure, ultimately leading to most of the deterioration in concrete structures. Hence, understanding the permeability of ions within the concrete microstructure is a crucial aspect of durability design and preventing concrete deterioration.

The durability of a concrete structure is determined by the intrinsic and extrinsic factors that make up the concrete system and the aggressiveness of the exposure environment (Ballim, Alexander & Beushausen, 2009). The intrinsic factors are those found within the concrete matrix and affect the concrete system itself, and extrinsic factors are those caused by the aggressiveness of the exposure environment, as illustrated in Figure 2-18. In this research, the intrinsic factor is the type of aggregate used and the influence on transport properties caused by the nature and concentration of the aggressive agents under exposure environment.

The durability of concrete is influenced by its penetrability, resulting from various mix factors such as water/cement ratio, compaction and curing methods, cement type, use of admixtures, age of concrete and the size, shape, and source of the aggregates.

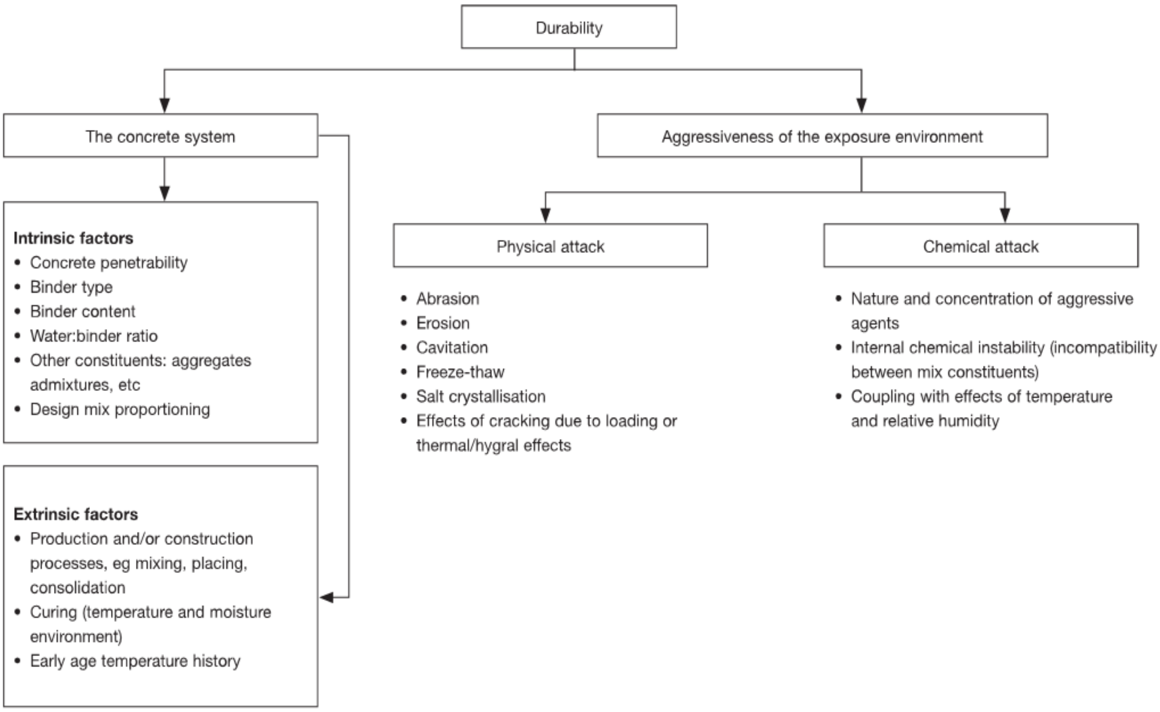


Figure 2-18: Factors influencing the durability of concrete by (Ballim, Alexander & Beushausen, 2009)

Since the cement paste largely controls the porosity, and the pore matrix and connectivity are dependent on the water-cement ratio and the degree of hydration, it is essential to consider these factors for durability measures. One of the techniques used to improve the durability of concrete includes lowering the capillary pore connectivity so that there is no transportation of fluid substances or introducing chemically reactive binding sites that can prevent the transport of aggressive ions (Kumar, Verma & Nasrin, 2017). The penetration rate of dissolved aggressive ions into its matrix affects the durability of concrete. The ease of transportation of dissolved aggressive ions through the concrete matrix directly influences reinforced and unreinforced concrete deterioration.

The active hypothesis for this research study investigates the influence on durability properties of concrete made with RAC through the effect of extra cement paste and absorbed water that can, later on, be released into the matrix. The presence of adhered mortar fosters a secondary reaction by providing excess cement paste and absorbed water that can increase the concrete's strength and thus increase the time for aggressive ions to penetrate the concrete mix. These two aspects increase the time for aggressive substances to initiate the reaction with components inside the concrete and delay the deterioration processes.

Furthermore, the necessity to investigate concrete's mechanical and durability properties originates from the reported strength increase and delay in transportation of aggressive substances from outside the concrete.

The deterioration mechanism on unreinforced concrete occurs through chemical attacks and leaching of expansive products such as gypsum and ettringite. In reinforced concrete, the deterioration mechanism occurs through similar processes as unreinforced concrete with the addition of carbonation and chloride ingress. These mechanisms depend on the transport properties of ions to move into the concrete. Concrete deterioration is primarily influenced by the transportation mechanisms of ions from the atmosphere into the microstructure of the concrete. Although there is a broad correlation between concrete strength and durability, concrete durability does not only depend on the strength of the concrete, as illustrated in Figure 2-19. Additionally, these assumptions are considered due to the weight of research showing concrete structures' early degradation.

It has been reported by (Alexander, Bentur & Mindess, 2017) that during their service life, various modern concrete structures require extensive repairs and maintenance, with costs to the economy ranging from 3% to 5% of gross national product in some countries. Poor knowledge of degradation processes by designers, insufficient acceptance standards for concrete on-site, and changes in cement characteristics and building techniques are some of the factors for the wide range in achieving durability performance.

As mentioned earlier in section 2.4, the versatility of concrete materials illustrates the need for independent durability and service life design. This versatility has exemplified that modern construction is subject to weathering and aggressiveness of the environment (Ballim, Alexander & Beushausen, 2009), and therefore different environments cause different deteriorations of concrete.

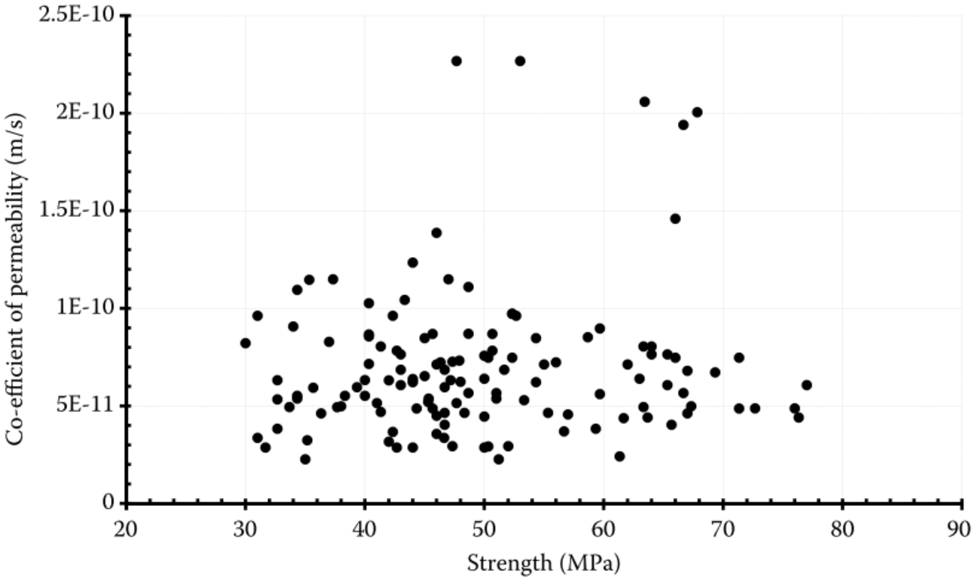


Figure 2-19: Relationship between the coefficient of permeability (Darcy k-value) and strength of concrete (Alexander, Bentur & Mindess, 2017).

Furthermore, advancements in present concrete technology, such as changes in structural design like members with reduced overall weight, contribute to the need for durability design. And it has been demonstrated by (Alexander, Bentur & Mindess, 2017) that there is no link between permeability (Darcy k value) and concrete compressive strength in actual construction, as illustrated in Figure 2-19. Hence, it is paramount to shift material design requirements from structural performance to designing materials for structural and durability performance.

Alexander, Bentur & Mindess (2017) report on the need for a new approach to dealing with durability caused problems in concrete applications. A more reliable approach is to specify and control durability by considering the following factors: the material used for concrete mix design, environmental condition of where the structure is built, serviceability and service life stresses, on-site quality of construction, and the optimum expected life of the structure.

A durability index practice has been established in South Africa to be able to enhance the quality of construction for reinforced concrete. The procedure measures the suitable transport properties of the concrete cover layer both in the laboratory and in-situ concrete, therefore illustrating the performance of concrete on both material potential and the quality of construction. Durability indicators are physical or technical measurable criteria that classify concrete according to the material, such as binder type, water-cement ratio, curing type and degree, processing factors, and exposure conditions. These indicators have developed to the extent of a reasonable durability design and performance-based specification in some cases of actual construction practices. When a relationship exists between index values and long-term performance properties, index testing could be used to govern concrete cover quality by defining limitations at an appropriate age. Hence, index tests will act as a parameter to assess the quality of construction work and provide a fair base of construction lifecycle costs under a range of environmental conditions (Alexander, Ballim & Stanish, 2008).

During this research, it was important to stress the relationship between the results on the material properties from the durability index tests and those from the long-term durability tests such as carbonation and bulk diffusion tests.

For instance, it has been reported by Mackechnie & Alexander (2002) that oxygen permeability index test values were more sensitive than compressive strength values in predicting the carbonation resistance of concrete. Mackechnie & Alexander (2002) investigated the early-age resistance of concrete to the transport of fluids and ions that affect reinforcement corrosion. A correlation between the early age characterization test and the performance-based durability from field data was established for concrete mixes with local materials denoted by: PC – Portland cement, FA – fly ash, and SL – blast-furnace slag. Figure 2-20 illustrates the correlations between oxygen permeability index values recorded at 28 days and carbonation depths after four years of exposure conditions.

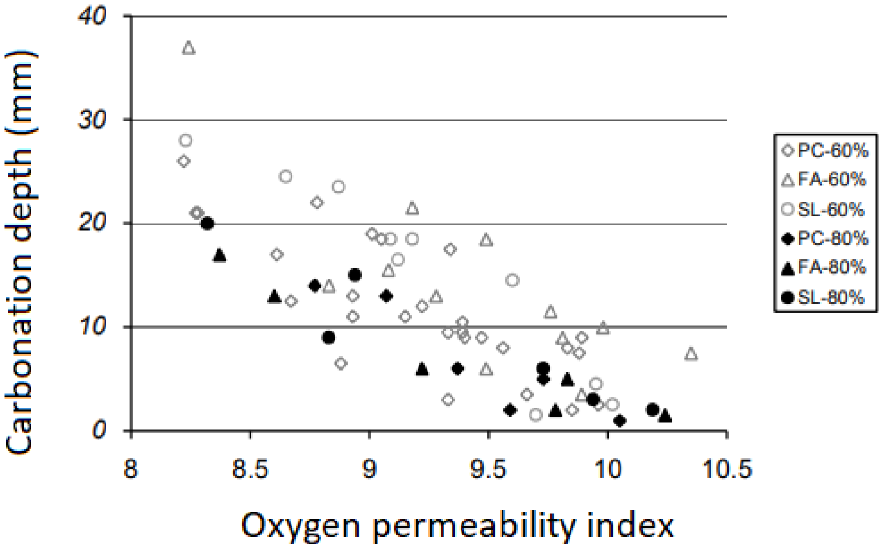


Figure 2-20: Relationship between oxygen permeability values and carbonation depth after four years of exposure (Mackechnie & Alexander, 2002)

2.9.1 Carbonation in concrete with natural aggregates

Carbonation is the reduction of the concrete alkalinity through carbon dioxide ingress. The carbonation process happens when atmospheric carbon dioxide dissolved in moisture diffuses into the concrete pore solution reacting with alkaline hydration products such as calcium hydroxide in the presence of water to form calcium carbonate *(Equation 1*) and (*Equation 2*).

$$CO_2 + H_2O \rightarrow H_2CO_3 \qquad \textit{(Equation 1)}$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow Ca\,CO_3 + 2H_2O \qquad \textit{(Equation 2)}$$

As the surface of the concrete becomes carbonated, this chemical reaction reduces the pH of the pore solution and advances slowly as a font until it reaches the reinforcement, destroying the passive ferric oxide layer surrounding the rebar; thus, corrosion propagates (Arito, 2012). This font or penetration depth is referred to as the carbonation depth, as observed in Figure 2-21. The carbonation depth progresses as long as moisture and carbon dioxide gas are present in the concrete matrix (Kumara & Kujur, 2014). Different studies have shown that, when neutralization of alkalis occurs, the pH of the pore solution, which is typically between 12.5 and 13.6, would reduce to a level lower than 9.5 (Bertolini et al., 2003; Ballim, Alexander & Beushausen, 2009; Trejo, Halmen & Reinschmidt, 2009)

The rate at which the carbonation depth develops is dependent on moisture content and relative humidity (RH). Salvoldi (2010) reports that the penetration depth progresses to carbonate the easily accessible portlandite portions of the concrete, followed by the rest of the cement carbonates as the carbon dioxide concentration increases. Later on, the higher concentration of carbon dioxide will force the hardly accessible cement to diffuse slowly to accessible parts of the concrete and ultimately carbonate.

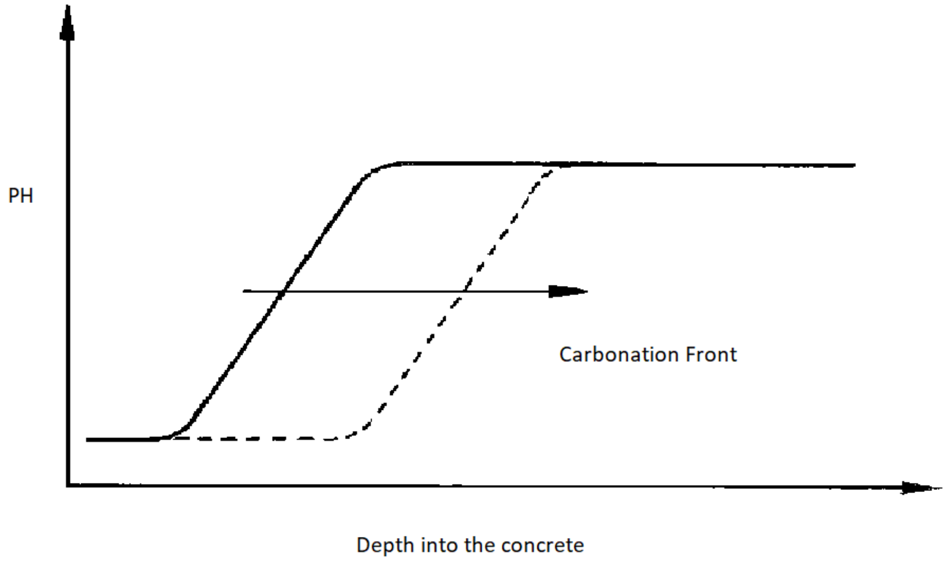


Figure 2-21: A figure illustrating the pH reduction on concrete due to the carbonation effect moving as a front (Ballim, Alexander & Beushausen, 2009)

At lower relative humidity, the penetration of carbon dioxide gas is at its peak; however, the reaction with alkaline products occurs in solution - in saturated concrete - and this condition has insufficient moisture to dissolve the carbon dioxide gas. At higher relative humidity, there is enough saturation for the alkaline products to occur in the solution, but the penetration of carbon dioxide gas is retarded due to complete saturation. The consequence of these two factors causes the carbonation process to be the highest in the moderate RH range (Poursaee, 2000).

Theoretically, carbonation depth doesn't extend beyond a specific point until all CaOH at that point has been converted to $CaCO_3$. Due to this fact, it is crucial to point out that this research investigates the influence of additional cement paste on the surface of recycled concrete aggregates to delay the carbonation process to progressing into the concrete matrix. During the carbonation test, by means of phenolphthalein application, the test measures the penetration depth of carbon dioxide, the depth in pH level and colour change below the pH of 8.2.

Similarly to the two-way system summarised by Ballim, Alexander & Beushausen (2009), the European Standard 206 and its complimentary British standard 8500 generalize two significant factors affecting concrete carbonation: environmental factors and intrinsic factors. Various intrinsic factors are linked to the concrete pore microstructure and the amount and composition of cement present in the concrete mix that affects the binding capacity of the compounds within the concrete. For instance, the addition of recycled fine aggregates in concrete mixes can be grouped as an intrinsic factor in the carbonation effect. In South Africa, the environmental classes adopted for the service life model of carbonation are as illustrated in Table 2-6.

The service life models for carbonation and chloride-induced corrosion permit a concrete structure's expected life based on the environmental conditions, cover thickness, and concrete quality (Alexander, Ballim & Stanish, 2008). During carbonation, the main transport mechanism in concrete is diffusion, which occurs through its porous system, described using Fick’s first law as illustrated in *(Equation 3*). It is considered that the carbonation rate is proportioned to the square root of the time of exposure with a constant factor that can be calculated (Ballim, Alexander & Beushausen, 2009; Silva et al., 2015).

$$X = K\sqrt{t} \qquad \textit{(Equation 3)}$$

In this equation, K is a parameter that takes into account all factors affecting carbonation measured in (mm/year$^{1/2}$), X is the carbonation depth measured in (mm), and t is the exposure time to carbonation measured in (year). The coefficient K is a proportionate measure of concrete carbonation resistance and the most convenient and accurate metric for characterizing the impact of concrete intrinsic variables on carbonation, particularly carbon dioxide levels, under the same environmental conditions (Ballim, Alexander & Beushausen, 2009).

The formula is obtained by integrating the diffusion equation and assuming that carbon dioxide level, the amount of carbon dioxide required to carbonate a unit volume of concrete, and the diffusion coefficient for carbon dioxide through carbonated concrete are all constants. Furthermore, a total reaction occurs before carbonation proceeds (Alexander, Bentur & Mindess, 2017).

However, it is reported by (Silva et al., 2015) that carbon dioxide concentration is not constant over time; the diffusion coefficient is subject to its relative humidity and drying and wetting cycles. Also, the amount of carbon dioxide for a unit volume of concrete to carbonate depends on the amount of carbon dioxide present inside the concrete matrix. And due to the difference between compounds reacting with carbon dioxide in high and low concentrations, whereas in low concentrations, only hydrated cement reacts with carbon dioxide, while in high concentrations, both hydrated and anhydrous cement react with carbon dioxide.

In order to investigate the carbonation resistance integrated with timely outcomes, an accelerated test is required to expose different concentrations of carbon dioxide levels (Silva et al., 2015).

Table 2-6: Environmental classes of concrete structures according to the EN 206

Classes	Environment conditions	Effects on concrete
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact ‘Many’ foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

2.9.2 Chloride ingress in concrete made with natural aggregates

Chloride ingress is the transportation of chloride ions through pores into porous concrete. Chloride ions are transported into the concrete from both internal and external sources. Examples of internal sources are salt-contaminated aggregates such as beach sand and admixtures such as calcium chloride. While external sources of chloride come from seawater, salt spray on maritime structures, de-icing salts on roads and bridges, exposure to industrial brine, and PVC fires which produces hydrogen chloride gas (Arito, 2012).

Chloride ions are transported in concrete through various mechanisms, such as diffusion, sorptivity, convection, permeation, and accelerated diffusion or migration. Diffusion is the primary mechanism for chloride transportation in concrete structures exposed to salt contaminated environments. The diffusion mechanism also governs the transfer of oxygen from concrete to the surface of the steel. In laboratory accelerated chloride tests, the migration transport mechanism is utilized to illustrate the movement of ions in a solution under an electrical field.

The diffusion mechanism is practically modelled through Fick's second law of diffusion illustrated in (*Equation 4*). Using reduced penetration equations that reflect the predominant penetration processes, time-dependent chloride penetration may be estimated. The most crucial material parameter in such a simulation may be the adequate diffusion coefficient D; for example, it is a basic form as explained by (Schiessl, 1996) as seen in (*Equation 4*). The most prevalent way to express chloride concentrations in the concrete matrix is as a percentage by mass of cement.

$$\frac{\partial C}{\partial t} = D.\frac{\partial^2 C}{\partial x^2} \qquad (\textit{Equation 4})$$

This equation represents the diffusion model for the penetration depth of chlorides (critical chloride content) in concrete. D is the effective diffusion coefficient, t is the time factor, C is the fluid concentration, and x is the penetration distance inside the concrete. The equation is governed by boundary conditions for the fluid concentration of Cx (chloride concentration at depth x at time t) and Cs (surface chloride concentration). Fick's second law may be expressed using Crank's error function (also known as Gauss error function), as illustrated in (*Equation 5*).

$$C_{x,t} = C_s[\,1 - \mathrm{erf}(\frac{x}{2\sqrt{D_a t}})\,] \qquad (\textit{Equation 5})$$

Whereas $C_{x,t}$ is the chloride concentration at depth x at time t, Cs is the surface chloride concentration (g/m3), erf is the mathematical error function, x is the distance (m), Da is the apparent chloride diffusion coefficient (m^2/s), and t is the time of exposure (s). Fick's second law of diffusion may be used to determine the diffusion coefficient based on the observed chloride profile and the surface chloride concentration on the concrete.

The rate of penetration of chloride ingress is affected by several factors, including the concrete's composition, water-binder ratio, pore structure, and the interaction between the pore matrix and the surrounding environment. In reinforced concrete, free chloride ions destroy the passive layer on the reinforcement and release the chloride ions, as illustrated in *(Equation 6*) and (*Equation 7).* The presence of moisture in the concrete pore structure facilitates the diffusion of chloride ions into the concrete. The rate of diffusion increases as the moisture content and availability of oxygen increases in the concrete matrix.

Chlorides exist in two forms inside the concrete matrix. Those that are free/mobile are readily available for corrosion propagation found in concrete pore solution and those bound within the binder matrix, removing the total number of chlorides available to corrode the concrete by binding with the cement matrix. These bound chlorides reduce the time for corrosion by removing chloride ions present in the concrete pore solution by interaction with the binder matrix. To some extent, all types of cement bind chloride ions, significantly impacting the rates at which chlorides from external sources permeate the concrete. These chlorides are either chemically bound by reacting with the aluminate phases of cement hydration (Tricalcium aluminate C_3A and Tetra Calcium aluminoferrite C_4AF) or physically bound through absorption.

Both forms of chlorides are in chemical equilibrium with each other except when, initially, the concrete is corroded by chloride contamination and begins carbonating hence lowering the pH of the concrete, causing a release of bound chlorides into the concrete pore solution (Alexander, Bentur & Mindess, 2017). It should be noted that the cementitious binders chemically bind some of the chlorides that enter the concrete, and depassivation occurs only when a threshold concentration of free chlorides is achieved at the reinforcement level. Due to this fact, it is essential to point out that this research investigates the influence of additional cement paste found on the surface of recycled concrete aggregates to delay depassivation and occurrence of threshold level hence longer time for free chlorides to reach the reinforcement level.

$$2Fe + 6Cl^- \leftrightarrow 2FeCl_3{}^- + 4e^- \qquad (\textit{Equation 6})$$

$$2FeCl_3{}^- + 4OH^- \leftrightarrow 2Fe(OH)_2 + 6Cl^- \qquad (\textit{Equation 7})$$

The fundamental mitigation measures against concrete deterioration, as described and structured by (RILEM), are to prevent response mechanisms or to use optimal design and material selection. The study of carbonation and chloride ingress is typical because they are mainly responsible for reinforcement corrosion in concrete, followed by fewer alkali-aggregate reactions or sulfate-induced expansion cases (P & Monteiro, 2006).

The bulk of this section focuses on carbonation and chloride ingress of concrete made with recycled concrete aggregates. Furthermore, how can replacing recycled fine aggregates in new concrete production influence the durability properties of concrete under these two aspects? It is reported that the porosity and water absorption of recycled concrete aggregates have a significant influence on the durability of concrete made with recycled concrete aggregates (Ridzuan et al., 2005; González-Taboada et al., 2016; Ismail, Kwan & Ramli, 2017; Kim et al., 2019). However, one of the most critical degradation phenomena in reinforced concrete is reinforcement corrosion, mainly caused by carbonation penetration and chloride ingress by eliminating the passive coating on reinforcement.

2.9.3 Carbonation of concrete made with recycled concrete aggregates

As mentioned in section 2.9.1 of this chapter, carbonation is the reaction between the atmospheric carbon dioxide and the calcium hydroxide from cement hydration to form calcium carbonate in the presence of adequate moisture, relative humidity and environmental CO_2. The carbonation process moves through a front within the concrete matrix. And this front is slowed down by a denser microstructure, less porous concrete, and greater content of calcium hydroxide content from the cement hardened paste. The carbonation front only progresses after all the cement paste at a particular location has been utilized (Ballim, Alexander & Beushausen, 2009). This progression suggests that the amount of calcium hydroxide present in the concrete pore structure influences the carbonation rate.

With regard to concrete with RCA, assuming all other mix variables are equal, the porosity of RCA is significantly greater than that of NAC for the same water binder ratio because RCA has more water absorption than natural aggregates due to the adhered mortar hence lowering RCA's carbonation resistance (Silva et al., 2015). A vast amount of research has been conducted on carbonation resistance for concrete made with recycled coarse aggregates (Ridzuan et al., 2005; Xiao, Lei & Zhang, 2012; Xiao et al., 2014; Silva et al., 2015). However, only marginal work is reported on the carbonation resistance of concrete made with recycled fine aggregates. This discrepancy is due to their reported higher porosity caused by the higher percentage of attached mortar found in their small particles compared to the recycled coarse aggregates. It should be noted that although some substantial work has been conducted on concrete made with recycled fine aggregates, all involve the use of modification methods such as pre-soaking the aggregates, superplasticizers and the use of adequate water/cement ratio.

Evangelista & de Brito (2010) studied the influence between reference concrete (RC), concrete with 30% (C30R) and 100% (C100R) replacement levels of RFA with exactly the same composition and grading curve in order to draw some conclusions on the feasibility of using recycled concrete aggregates in structural concrete. It was observed that the carbonation resistance is lowered with the use of recycled fine aggregates, as observed in Figure 2-22. As the replacement of natural aggregates increases, the carbonation resistance decreases. He observed that the carbonation depth penetration progressed 40% more in concrete with a 30% replacement value of natural aggregates with recycled fine aggregates.

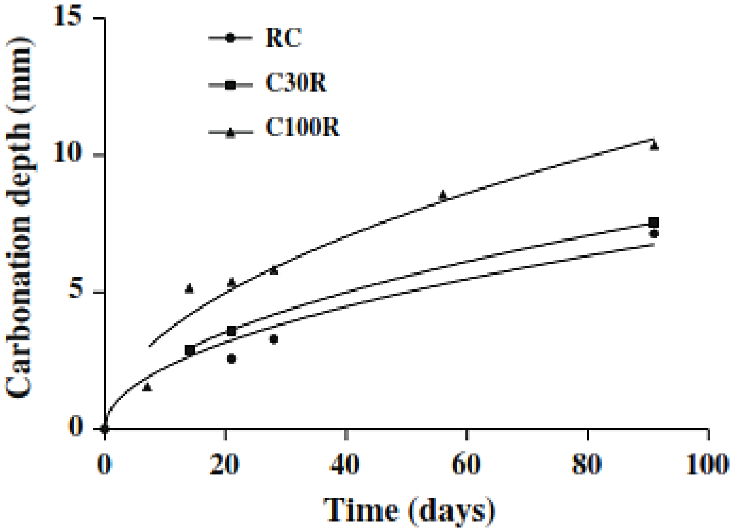


Figure 2-22:A graph illustrating carbonation depth versus time for three replacement levels of RFA (Evangelista & de Brito, 2010)

Furthermore, Silva et al. (2015) summarises ten publications reporting on the influence of carbonation depth on various replacement levels of both coarse and fine RCA. For the replacement of fine RCA, their work illustrated that incorporating recycled fine aggregates increased the carbonation depth to 8.7 times that of natural aggregates, as seen in *Figure 2-23*. The increase is subject to the fact that recycled fine aggregates absorb more water than natural aggregates due to the adhered mortar and increase the permeability of the resultant concrete.

Contrary to these findings, Pedro, de Brito & Evangelista (2017) investigated the long-term durability properties of incorporating both, fine and coarse recycled concrete aggregates in structural concrete and found that it was feasible to achieve comparable concrete performance utilising different sources of concrete while maintaining the same compressive strength.

Regarding resistance to carbonation resistance, it was observed that, at 28 and 91 days, the difference in carbonation depths between reference concrete and RAC with 25% and 50% recycled fine aggregates did not exceed 1.1 - 1.5 mm and 3.2 - 3.6 mm, respectively. Although it was reported that the finer fraction led to more than 36% dispersion when utilized solely due to their higher porosity, the long-term durability was comparable to those of natural aggregates.

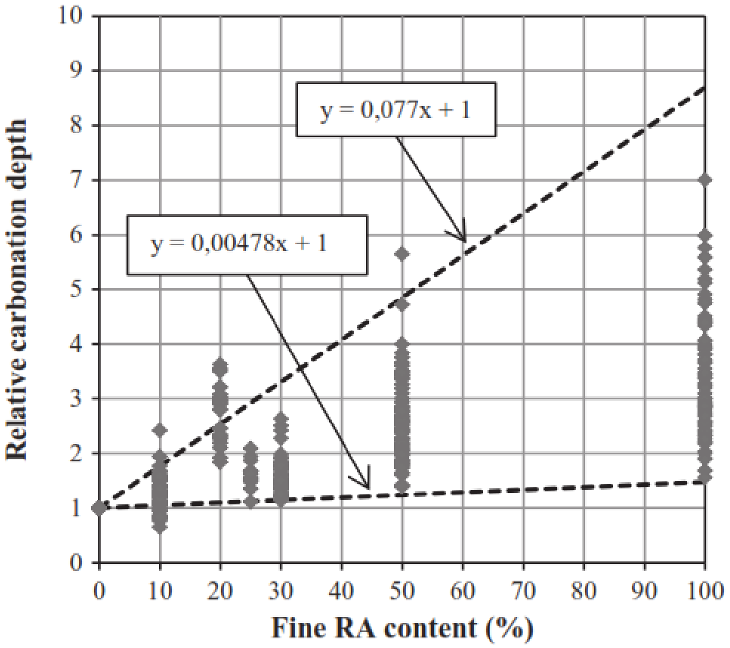


Figure 2-23: The relationship between carbonation depth and replacement levels of recycled fine aggregates (Silva et al., 2015)

A similar trend was reported by Leemann & Loser (2019) investigated the carbonation resistance of recycled aggregate concrete using two types of the recycled aggregate of grain size (0 -16 mm, and 0-32 mm) in order to clarify the influence that replacement values had on new concrete applications. It was concluded that carbonation resistance could be reduced due to some extremely porous or previously carbonated recycled aggregate particles. For concrete made with RA of the same compressive strength, no increase in carbonation resistance was observed for RCA's 25% and 50% replacement levels. In addition, there was no systematic difference between the carbonation susceptibility and compressive strength of the concrete made with dry or pre-saturated aggregate particles (Leemann & Loser, 2019).

Additionally, Kirthika & Singh (2020) researched the durability studies of concrete made with recycled fine aggregates concrete concluded that 30% replacement of recycled fine aggregates attains 5% less carbonation depth than conventional concrete. These results were attributed to the improvement in concrete microstructure due to an un-hydrated cement paste that consumes more water. As a result of the deposition of $CaCO_3$ in the voids within the cement matrix, this procedure resulted in decreased permeability, hence inhibiting more carbon dioxide in concrete. A similar observation was reported by (Kumar, Gurram & Minocha, 2017) while assessing the influence of recycled fine aggregates on concrete microstructure. They concluded that the hydration process for concrete mixes with 100% RFA occurred at a different rate to concrete with 0% RFA due to the increased amount of un-hydrated cement paste and calcium hydroxide crystals present in the concrete with 100% RFA.

Further work on concrete made with recycled fine aggregates by (Zega & Di Maio, 2011) investigated the use of RFA in concrete with durable requirements. The limited usage of recycled fine aggregates and the viability of its utilization owing to increased economic significance and scarcity of natural fine aggregates for concrete production are addressed in this study. Three replacement values of RFA (0%, 20% and 30%), effective water binder ratio and water reducing admixture are utilized. It was concluded that the carbonation depths on concrete with RFA are similar to those of concrete without RFA at the ages of 310 and 620 days due to the lower effective water/cement ratio of RFA concretes.

In this case, the lower effective water binder ratio of RFA concretes is due to the high water absorption capacity of RFA, which certainly influences reduced porosity and is able to compensate for the use of a more porous aggregate (Corinaldesi & Moriconi, 2009).

Various researchers reported a similar trend in concrete made with recycled coarse aggregates. A study to determine the correlation between carbonation resistance and compressive strength of recycled aggregates concrete was done by Xiao, Lei & Zhang, 2012; and Xiao et al., 2014. They observed that recycled concrete aggregates with higher compressive values had similar carbonation depths to conventional concrete. Recycled concrete aggregates originating from compressive strength values of 20 MPa, 30 MPa, and 50 MPa recorded carbonation depths of 80%, 26% and 10% higher, respectively. Therefore, concluding that the source of recycled concrete aggregates plays a crucial role in the durability of concrete made with recycled concrete aggregates. Further analysis by Xiao, Lei & Zhang (2012) argued that because RCA contains old adhering mortar, the overall cement content of RAC is higher than that of NAC, implying that there is more clinker content/cement available for carbonation, increasing RAC's carbonation resistance.

Other reports by Eguchi et al., 2007; and Thomas et al., 2013 on concrete mixes with recycled coarse aggregates showed a similar or higher carbonation resistance than concrete without recycled aggregates. Eguchi et al., 2007 reported that the carbonation depth decreases in concrete with higher percentages of recycled coarse aggregates. Similarly, (Thomas et al., 2013) reported no significant increase in carbonation rate with the RCA incorporation.

The main focus of this research is the presence of additional cement paste found on the surface of the recycled fine aggregates, which could slow the progression of carbon dioxide ions into the concrete matrix. It should also be noted that no modification technique was used during the adaptation of RFA in this research.

2.9.4 Chloride penetration of concrete with recycled concrete aggregates

As elaborated in section 2.9.2, chlorides get into the concrete in three main ways: by solution form into the concrete (chloride ingress), in the mixing stage either through contaminated aggregates or mixing water and at the casting stage as a contaminant of the reinforcement. Hence, the absorption property of the concrete microstructure is a crucial factor when designing durable concrete.

The level of absorption and the amount of free chlorides available in the concrete microstructure determine how quick or slow the deterioration processes occur during the chloride ion penetration. It has been reported that since recycled concrete aggregates contain a layer of mortar on the parent aggregates, they tend to have higher absorption properties than natural aggregates (Ferreira, De Brito & Barra, 2011; James Mackechnie & Munn, 2011; Thomas, Thaickavil & Wilson, 2018; Thomas et al., 2019). However, it has been reported that there is the presence of unhydrated cement on the surface of recycled concrete aggregates, which can bind more chlorides and increase deterioration time (Li, Xiao & Zhu, 2016; Kumar, Gurram & Minocha, 2017).

Additionally, the deterioration processes in concrete caused by either carbonation or chloride ingress move through a font or have to reach a threshold level for deterioration to initiate, respectively. Hence, if the adhered mortar contains unhydrated cement, the deterioration process could take a long time to deteriorate for concrete with recycled aggregates compared to concrete with natural aggregates. This prediction forms the foundation of the hypothesis for this research work.

Similar to carbonation resistance, numerous publications have reported on chloride penetration resistance for concrete made with recycled coarse aggregates compared to concrete made with recycled fine aggregates (Limbachiya, Leelawat & Dhir, 2000; Sagoe-Crentsil, Brown & Taylor, 2001; Kou & Poon, 2012, 2013; Vasco et al., 2015; Xuan, Zhan & Poon, 2017; Dimitriou, Savva & Petrou, 2018; Guo et al., 2018; Neves et al., 2018; Thomas, Thaickavil & Wilson, 2018; Thomas et al., 2019). Furthermore, all reported work involves the use of modification methods such as pre-soaking the aggregates, superplasticizers and the use of an effective water/cement ratio.

Various research reports on the decrease of chloride ion penetration resistance when recycled aggregates are used in new concrete applications and when the percentage of RAC replacement increases. This trend is commonly justified by the permeable nature of recycled aggregates, which causes a decrease in resistance of chloride penetration into the concrete microstructure (Evangelista & de Brito, 2010; Bravo et al., 2015; Pedro, de Brito & Evangelista, 2017; Liang et al., 2019; Kirthika & Singh, 2020; Nedeljkovi et al., 2021).

Evangelista & de Brito (2010) investigated the influence of migration coefficient in concrete made with recycled fine aggregates through the use of particle sizes up to 1.19 mm and an effective water binder ratio. He observed a 12% and 33.8% increase in the migration coefficient in concrete with 30% and 100% replacement levels of recycled fine aggregates compared to concrete without recycled fine aggregates, respectively. The migration coefficient increase was attributed to the increase in concrete porosity due to the increase in the proportion of recycled fine aggregates that were reported to be more porous than the natural aggregates. A similar observation was made by Pedro, de Brito & Evangelista (2017) on the increase of migration coefficient for concrete made with RFA compared to concrete without RFA.

Studies on the chloride permeability of recycled aggregate concrete by (Kou, Poon & Chan, 2007; Berndt, 2009) demonstrated that the recycled coarse aggregate replacement percent significantly impacts the chloride permeability of RAC. They found that chloride penetrability coefficient and diffusion coefficient increased linearly in mixes with recycled concrete aggregates. These results, however, were still acceptable for durability requirements.

Kou & Poon (2013) investigated the long-term durability properties of recycled aggregate concrete prepared with the addition of fly ash. They summarise that the concrete’s microstructure becomes more durable against the aggressivity of the environment after a period of time and curing age for concrete made with recycled concrete aggregates. In regard to chloride resistance, their work illustrated that the increase of recycled concrete aggregates lowered chloride ion penetration resistance at different curing ages. However, after ten years of casting, the chloride ion penetration was similar to concrete without recycled concrete aggregates as the recycled concrete aggregates increased.

Vasco et al. (2015) presented a statistical analysis on the influence of substituting natural aggregates (NAC) with recycled concrete aggregates at 50% (RAC-50) and 100% (RAC-100) on the chloride ion migration and total charge passed of concrete. It was observed that for concrete with the same compressive strength, the resistance of concrete with recycled concrete aggregates to chloride ion penetration was similar to that of concrete without recycled concrete aggregates. As a result, Vasco et al. (2015) work showed that the chloride movement coefficient and the total amount of charge passed might be estimated purely based on the strength class of the concrete. Hence, making it easier to design concrete structures with more performance-based approaches. They observed that lowering the water binder ratio of the concrete mixes with recycled concrete aggregates and mineral additions such as fly ash could also improve the chloride resistance. In the laboratory, the resistance of the concrete specimens to chloride-ion penetration is illustrated as the total charge passed in coulombs in a sample specimen as seen in Figure 2-24.

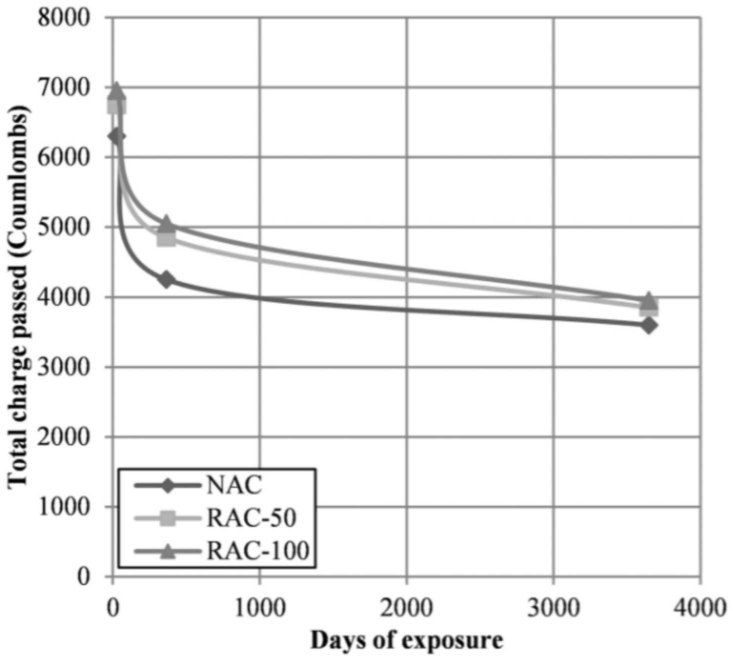


Figure 2-24: The total number of charges passed in coulombs against the curing ages (Vasco et al., 2015)

Contrastingly, it should be noted that various other studies have also illustrated that the chloride ion resistance in concrete with recycled fine aggregates is higher than in concrete without recycled fine aggregates (Vasco et al., 2015; Guo et al., 2018; Wang et al., 2018).

Guo et al. (2018) showed that when concrete with recycled fine aggregates is made with a low water binder ratio, it illustrates better durability properties against chloride ion penetration than concrete without recycled concrete aggregates. He concludes that the result is due to the additional C-S-H cement component present on the surface of recycled concrete aggregates, which facilitates chloride binding and thus delays concrete degradation. The incorporation of recycled fine aggregates in concrete can modify the penetration rate of carbon dioxide and chloride ions into the concrete.

Kirthika & Singh (2020) summarises that chloride ion penetration is directly connected to the volume fraction of RFA in concrete, and the penetration rate increases with an increase in RFA content. The study illustrated a 21.25% higher resistance to chlorine penetration at 30% RFA than river sand concrete, whereas 50% RFA had a 25% lower resistance than control concrete at 28 days. It was reported that the lower resistance in higher replacement levels was because of the extra free water content in RFA than control concrete resulting in a porous microstructure. Moreover, the presence of adhered cement paste in RFA reveals a poor microstructure resulting in weak ITZ and the presence of voids.

However, as the concrete matures, resistance to chlorine penetration increases irrespective of RFA content. Hence, compared to 28 days, higher chloride resistance was observed at 56 days. Similar to the work of Guo et al. (2018), the increase was attributed to the higher amount of Calcium Silicate Hydrate (CSH) formation making the concrete dense microstructure and filling the voids. Similar to 28 days, the chloride resistance at 30% was higher than that at 50% replacement of RFA.

Additionally, Zaharieva et al. (2003) summarised that recycled aggregates might be categorized as average quality rather than low quality using the standard practices for conventional concrete. Although RFA is a lower-quality aggregate with a detrimental impact on concrete material characteristics, substantial experimental work revealed that RCA can still be utilized.

For most research work, it has been reported that since the results fall into the required specifications, the use of recycled concrete for structural concrete can be a viable option. However, much emphasis is highlighted on the variability in the material's source, porosity and aggregates agglomeration in the concrete mix and hence more testing needs to be conducted for broader applicability. And in summary, this research will investigate the influence of concrete made with fine recycled aggregates while subjected to aggressive ions.

2.10 Chapter summary

As a summary of the chapter, some critical insights were highlighted in this section to form the basis for the methodology adopted in this study.

Gagg (2014) reported that for each 7.7 billion people, about 3 tons per year of concrete is utilized. This high consumption of non-renewable natural resources has increased the possibility of exhaustion due to the high volume of concrete production as the principal building material in construction projects. Similarly, these activities have also increased the amount of construction and demolition waste generated in the construction industry.

Sustainable cement production and the use of secondary products such as recycled materials have been some of the forefront measures to attain durable structures and maintain a greener environment. Similarly, these activities have substantially contributed to the effects of the deterioration of concrete structures in general.

Since aggregates constitute about 60 -70% of the concrete mass, an effective strategy for recycling construction and demolition wastes as recycled aggregates will lift the burden on the demand for natural materials. Most scholars have reported using C&DW as recycled concrete aggregates, mainly focusing on the coarse fraction compared to the fine fraction. Owing to advantages such as less variability found in the sourcing of the material, environmental exposure and strength of the material, lower water absorption rate and less contamination from the finer particles compared to the fine fraction.

In addition, it should be noted that various modifications have been adopted for the use of recycled concrete aggregates in concrete production to meet certain standards. These limitations and modifications include limiting the replacement of recycled concrete aggregates (RCA) to less than 30% of the volume of aggregates, pre-soaking of the material before mixing, introducing a two-stage mixing approach to cater for the higher water absorption property of RCA, the use of mineral additives as well as the use of water reducing superplasticizers (Evangelista & de Brito, 2010; Silva et al., 2015; Dimitriou, Savva & Petrou, 2018; Rajhans et al., 2019).

However, this study focused on using C&DW as fine aggregates with no modifications to the mix design. This technique was done by investigating the influence of replacing natural fine aggregates on the durability and other properties of concrete made with recycled fine aggregates. As seen in hypothesized in Figure 1-1 b), due to the attached mortar found on the surface of the recycled fine aggregates, the transport of aggressive ions through the concrete matrix could affect the durability and other properties of concrete made with recycled fine aggregates.

This work aims to investigate the transport mechanism that causes concrete deterioration through durability properties, as observed in Figure 1-1. These reports form the basis of the experimental investigation conducted in chapter three of this study.

It can be concluded that the supposition that compressive strength replicates the durability properties of concrete is outdated. This assumption was mainly on the foundation that concrete with adequate water-cement ratio, sufficiently designed, compacted, and cured, will possess sufficient strength and durability. Given advancements in contemporary concrete technology, such as the vast range of binders available, alternative materials such as recycled concrete aggregates, changes in the structural design such as the existence of superstructures and increasingly aggressive environmental conditions, this approach to concrete durability is no longer appropriate. In order to adjust from basing concrete designs from the prescriptive approaches to performance-based approaches, which are inclusive of durability design, concrete constituents contribute significantly to the advancement of this strategy.

In addition, the advancement in technology and the overutilization of natural resources for concrete production have resulted in more demand for the use of alternative resources. Worldwide agendas such as the green initiative by the United Nations Environmental Programme (UNEP) emphasize minimising the environmental impact of construction through developing sustainable building strategies.

3 Research Methods

This chapter describes the experimental investigation conducted in the civil engineering laboratory at the University of Cape Town to investigate the hypothesis for this study. The study aimed to investigate the effect of partial replacement of fine natural aggregates with recycled fine aggregates (RFA) on concrete's durability and other properties. The investigation consisted of three main test stages: material characterization tests, concrete fresh property tests, and concrete hardened property tests. All the tests involved in each stage were conducted in accordance with South African National Standards (SANS) and, or the American Society for Testing and Materials standards (ASTM).

3.1 Experimental investigation

The experimental investigation was divided into four phases, as summarised in Figure 3-1. The descriptions and details of each stage are described in the following subsections. The tests conducted were for material characterization, fresh concrete properties, as well as mechanical and durability properties of hardened concrete.

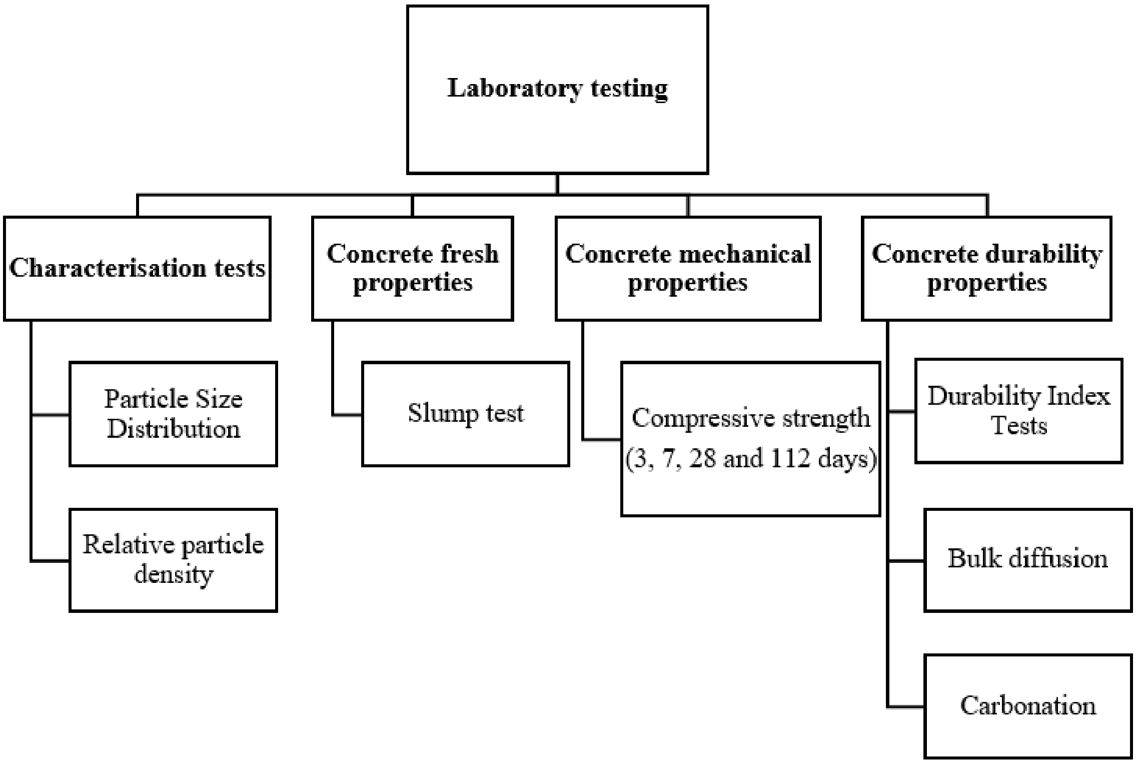


Figure 3-1: Schematic representing the experimental program conducted in the laboratory.

3.2 Materials

3.2.1 Cement

CEM II/A-L 52.5N, Portland limestone cement, was used for this research. This cement is manufactured by Pretoria Portland Cement (PPC) company limited and is commonly used in Western Cape construction projects. This type of cement is categorized in the SANS 50197-1 under the 52.5N strength class and consists of 8% of ground limestone addition percentage by mass. The properties of this cement are given in Table 3-1 and Table 3-2, sourced from the PPC AFRICA (2020) website.

Table 3-1: Physical properties of the cement used in this research (PPC AFRICA, 2020).

Physical properties	**Relative density**	**D (0.5) (μm)**	**Colour**	**Specific surface area (m^2/g)**	**Specific (Blaine) Area (m^2/kg)**
CEM II/A-L 52.5N	3.1	17.7	Grey	0.86	±400

Table 3-2: Chemical properties of the cement (%)

Chemical constituents	SiO_2	Al_2O	Fe_2O_3	Mn_2O_3	CaO	MgO_2	SO_3	**Other oxide**	**LOI**	**Total**
CEM II/A-L 52.5N	19,77	3.24	3.11	0.06	63.84	1.28	2.55	1.42	**4.63**	99.9

3.2.2 Water

Potable tap water was used for casting and curing the samples except for the bulk diffusion test, where distilled water was used to make up the chloride solution.

3.2.3 Admixtures

This subsection is included because various studies on recycled concrete aggregates suggest using admixtures to achieve standard workability due to their high-water absorption property. However, this research used no admixtures in the concrete mixes to have a similar basis for comparison. Concrete mix cohesiveness and segregation were to be investigated during this stage.

For this study to properly investigate and form a basis of comparison on the influence of adding a portion of recycled fine aggregates (RFA), superplasticizers would have been an additional variable in the concrete mixes. The use of superplasticizer would need to be accounted for towards any positive or negative results attained by concrete made with RFA compared to concrete without RFA. This limitation is because the addition of superplasticizer is through a per cent of cement mass in a mix. Superplasticizers or water reducers would help attain a more workable mix and contribute to any positive results obtained from the concrete mixes.

It should be noted that the concrete mixes were easily compacted using a vibrating table to attain adequate compaction of the concrete mixes before casting.

3.2.4 Coarse aggregates

The coarse aggregate adopted in this study was a greywacke aggregate of 19 mm nominal size crushed from fresh greywacke rock. Greywacke, also known as 'Malmesbury shale', consists of a fine-grained, glassy-like structure originating from a metamorphic rock. This hard and dense rock occurs through thermal metamorphism in close proximity to Cape Granite intrusions (Cole, Ngcofe & Halenyane, 2014).

The Malmesbury rocks are the oldest of the late Precambrian rocks formed of alternating dark grey, fine-grained greywacke sandstone and slate layers. Given the origin of the greywacke, it is reasonable to assume a progressive transformation from crystalline rock that is ideal for use in concrete to a less attractive shale product, which is in the opposite direction to the granite texture (Graham Grieve, 2009b). The greywacke stone of nominal particle size 19-mm was investigated on its physical properties, such as compacted bulk density, particle relative density and particle size distribution, using SANS 5845, SANS 5844, ASTM C136 and SANS 201, respectively. According to the standard, all three tests were investigated three times to assist in dealing with the variability in the material itself. All values are an average of three values conducted for the same test.

The physical properties of coarse aggregates used in this study are summarised in Table 3-3.

Table 3-3: Physical properties of Coarse Aggregate

Coarse aggregates	Stone size - 19mm nominal size
Compacted bulk density	1450 kg/m^3
Particle relative density	2.72

3.2.5 Fine aggregates

Three types of fine aggregate were used in this research, which made up the three variables in the concrete mixes; natural sand, Philippi dune sand, greywacke crusher sand, and recycled fine aggregates. The following subsections describe the characteristics, source, and reasons for using these fine aggregates.

The physical properties of fine aggregates were investigated according to SAN 201 and SANS 5844:2014 to determine fineness modulus, particle size distribution and particle relative density, respectively. During fine aggregates preparation, oven drying was adopted to ensure the aggregates were dry before continuing with the mixing phase. The drying procedure was done in an oven for 48 ± 2 hours at 50 °C.

3.2.5.1 Natural fine aggregates

A blend of Philippi dune sand and greywacke crusher sand was adopted for this study. This combination of naturally occurring materials is made due to gradation compliances that control the use of fine aggregates in the construction industry. Ideally, this is done to achieve a good gradation curve that would offer an optimized size range of aggregates.

Philippi dune sand is characterized by rounded to sub-rounded particles of aeolian origin, originating from coastal sand dunes. It consists of grains with a size lesser than 1,0 mm but larger than 0,1 mm, classifying the sand as fine aggregates. Owing to the strong erosive nature of the air movement, the sand grains are also well round-shaped, resulting in a lower water requirement of approximately 170 l/m^3 in a concrete mix. Initially, this sand was extracted from riverbeds and land quarries; however, a shift to the coastal and marine aggregates has inclined due to the depletion of inland sources (Walker & Alexander, 2013; UNEP, 2014).

Typical angular and flaky shapes characterize greywacke crusher sand; it comprises a partial gap graded distribution resulting from the crushing process (Walker & Alexander, 2013). Furthermore, according to the standard water requirement, crusher sand complies with 180 to 185 litres per cubic meter.

The combined use of these sands has been adopted in the Western Cape construction industry due to the sources of natural pit sand running out. Hence, due to compliance requirements with gradation, crushed greywacke and dune sand provided an excellent blend of fine aggregates. Therefore, this blend was adopted in this study to mimic the real-life construction practice in South Africa. A combination of 50:50 dune sand to crusher sand was used for the control sample.

3.2.5.2 Recycled fine aggregates

This section summarises the considerations taken during sourcing, the adaptability of the material and the mix design of concrete with recycled fine aggregates according to the active hypothesis adopted for this research study. A summary of the considerations made is illustrated in Table 3-4.

The percentages adopted for replacing natural fine aggregates with recycled fine aggregates in the concrete mixes were 0%, 25%, and 50%. This study's source of recycled aggregates consisted of concrete panels from a road expansion project found approximately 100 km from Cape Town (Figure 3-2). It should be noted that these panels were from a new construction project and not an old structure. The holes seen in the figure were drilled prior to extract concrete discs for carbonation testing.

Figure 3-2: N2 road expansion panels of (0.7m X 0.45m X 0.15 m) used as a source of recycled fine aggregates

Table 3-4: Summary of considerations for the use of recycled fine aggregates.

Feature	Factor dependent	Consideration made
Sourcing of material	Controlled vs uncontrolled environment	RFA was sourced from the concrete panels taken from a road expansion project. The environment is subject to aggressivity of weather and ions, which is categorized as an uncontrolled environment, whilst the testing was done in the laboratory, classified as a controlled environment.
Method of crushing	One stage vs two-stage crushing method	As part of the considerations adopted for the hypothesis of this study, the adhered mortar plays a major role in investigating the durability of RFA in concrete mixes. During the two-stage crushing, more adhered mortar is reduced from the surface of the aggregate as compared to the one-stage crushing method. Hence, one stage of crushing was adopted.
W/b ratio	Effective and apparent water content	Due to the high-water absorption property of RFA, some research suggests the use of effective water content. This concept is done by adding the amount of water absorbed by the RFA to the amount calculated during mix design. However, this study only utilized the apparent water content calculated during the mix design.

These panels were delivered to the UCT civil engineering laboratory for Durability Index testing. After the tests, the remainder of the panels is usually discarded. In order to utilize waste material from this project, the waste was collected, crushed, and the crushed material was sieved to obtain RFA that met this research's purpose, see Figure 3-5:.

The breaking process was conducted manually using handheld tools such as hammers to yield concrete pieces of a size range of 5 to 10 mm placed into the jaw crusher as seen in Figure 3-3 for further crushing into less than 4.75 mm. The crushed material was then collected and sieved to produce material with a maximum sieve size of 4.75 mm.

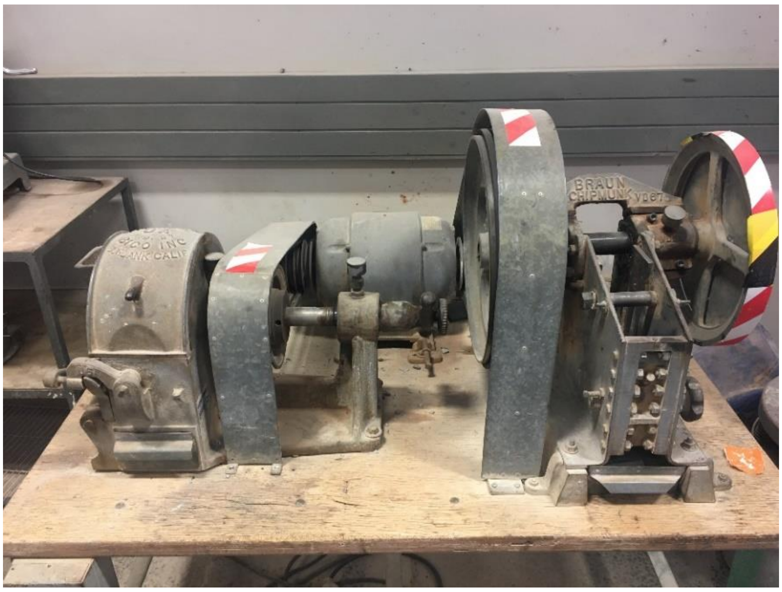


Figure 3-3: A picture of the jaw crusher used for crushing recycled fine aggregates.

Table 3-5: A summary of the compressive strength results for the original RFA

Core ID	**Heigh (mm)**	**Diameter (mm)**	**Area (mm2)**	**Mass (kg)**	**Density (kg/m3)**	**Load (KN)**	**Strength (N/mm2)**
CORE 1 C	102.485	102.485	7961.681	1.93	2370	295	37.10
CORE 1 B	102.285	102.285	8082.331	1.985	2400	315	39.00
CORE 1 A	102.055	102.055	8049.443	1.9	2310	250	31.10

The compressive strength results for the original RFA, had an average of 35.7 MPa.

Core ID	Heigh (mm)	Diameter (mm)	Area (mm2)	Mass (kg)	Density (kg/m3)	Load (KN)	Strength (N/mm2)
CORE 1 C	102.485	102.485	7961.681	1.93	2370	295	37.10
CORE 1 B	102.285	102.285	8082.331	1.985	2400	315	39.00
CORE 1 A	102.055	102.055	8049.443	1.9	2310	250	31.10

Table 3-5 summaries the results of each core tested.

3.3 Material characterization

Material characterization for this research was conducted through two tests — particle size distribution and relative density of the aggregates. The samples used for material characterization were prepared according to SANS 197. The procedure involves obtaining a specific amount of the bulk material and quartering it to acquire a final sample that is uniform and representative of the whole material. The preparation and characterization tests were done according to SANS 197, SANS 3001-AG23:2014, and SANS 201.

3.3.1 Particle size distribution and relative density tests

During the particle size distribution for all three types of fine aggregates, crusher sand, dune sand and recycled concrete aggregates, the materials were quartered, and 500 grams were utilized for the distribution procedure. Three samples of the same aggregate were used to achieve an average of one. This test was done according to SANS 197 and SANS 201. The amount of aggregates retained at each particular sieve size is as seen in Figure 3-5:. This standard provides a sieving approach for measuring the particle size distribution of coarse and fine aggregates down to 75 µm.

500 g of the sample material was placed in a dry and tared pycnometer during the relative density test. Afterwards, the pycnometer's neck was cleaned free from any loose sample, placed on a mass balance, and weighed (m_b). Enough water was filled into the pycnometer to cover

the sample while gently shaking and tapping the pycnometer to remove all air bubbles and voids in the sample. Subsequently, the pycnometer was filled to its calibrated capacity, and the contents weighed (m_c). After this stage, the contents were washed off, and the pycnometer was filled with water to its calibrated capacity and weighed (m_d). The pycnometer was thoroughly dried during the procedure and cleaned on the outside to prevent any excess mass gain. Three samples of the same aggregate were used to achieve an average sample value. The relative density of the fine aggregates was conducted according to SANS 3001-AG23:2014. The apparent particle density of the aggregates (δ_{pb}) was then calculated from *(Equation 8).*

$$\delta_{pb} = \frac{m_b}{m_b - (m_c - m_d)} \qquad \textit{(Equation 8)}$$

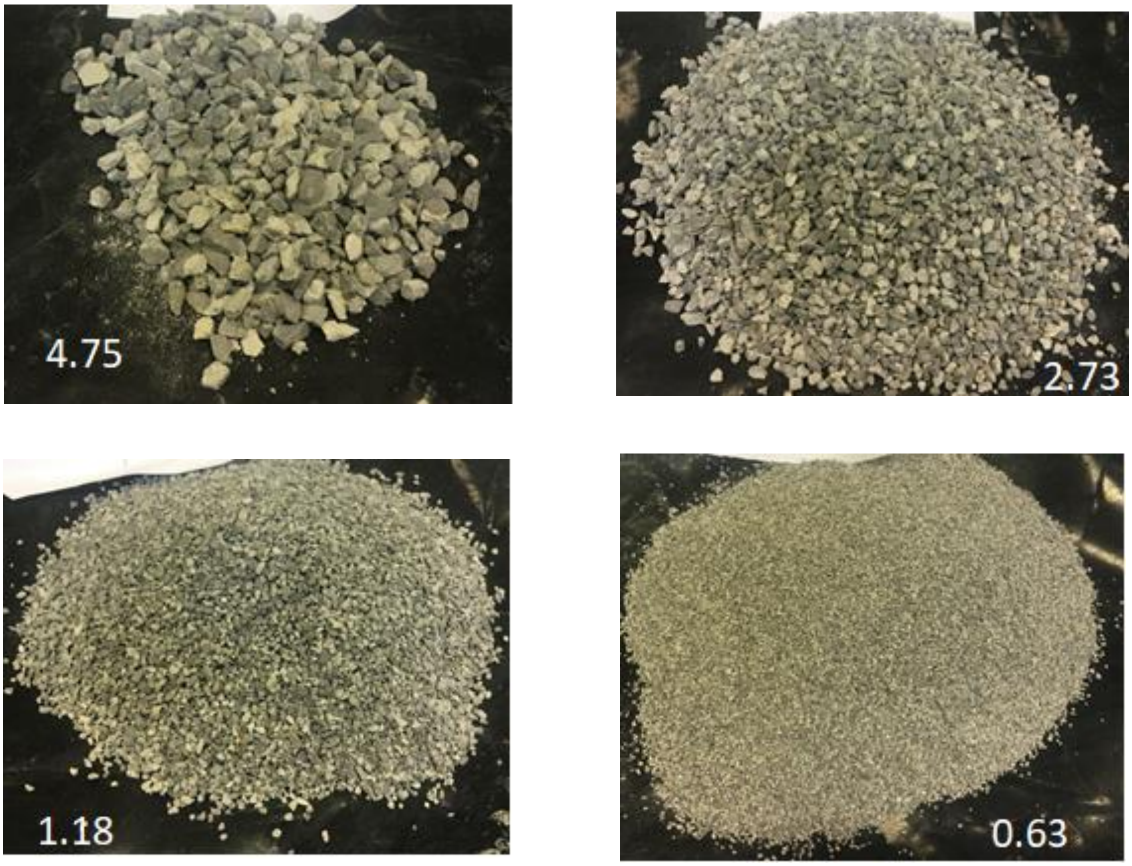


Figure 3-4: Particle size distribution of recycled concrete aggregates from sieve no 4.75 mm to 0.63 mm sieve

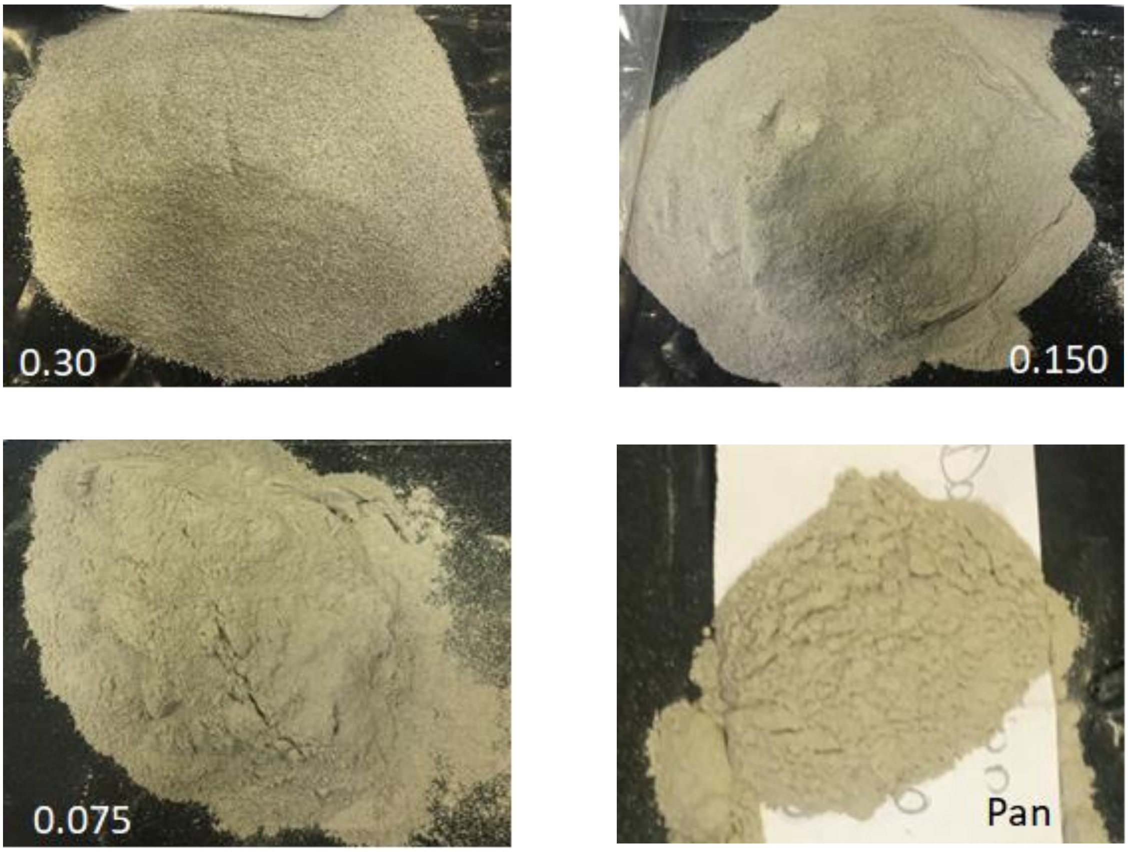


Figure 3-5: Particle size distribution of recycled concrete aggregates from sieve no 0.30 mm to the pan

3.4 A framework for the concrete mix design

Besides the water to binder ratio (w/b), concrete workability is a function of the fines included in the concrete mix; therefore, it depends on the characteristics of the fine aggregate used. Fine aggregates influence the amount of water required to make a specific volume of concrete. In a cubic metre of a concrete mix, when the size and type of stone, cement type, and uniformity of concrete are standardized, the amount of water used acts as a beneficial indicator in determining the properties of the sand in the concrete mix (Graham Grieve, 2009b).

The concept of Standard Water Requirement (SWR) was adopted to compare the different types of sand replacement quantities during concrete mix design. SWR is defined as the amount of water required to make one cubic metre of standard concrete constituents (Addis & Goodman, 2009). An effective formula was applied to the control design to maintain a standard cubic meter and vary the influence of recycled fine aggregate replacement, as seen in Table 3-7 and Table 3-8.

Two different considerations were made when conducting the concrete mix design, and therefore, both mix design A and mix design B were reported, and the reasons why mix design B was used were discussed. Mix design A was inconsistent with the SWR as the replacement value of recycled fine aggregates increased. Coarse aggregates changed in volume as the percentage of recycled fine aggregates increased, defying from the standard cubic metre of the concrete mix concept. Thus, mix design A was not adopted for this study as it presented a new variable in the mix.

On the other hand, mix design B considered this changing volume of coarse aggregates; in this way, making the other constituent's volume constant and only varied the amount of fine aggregates in the mixes. Both mix designs were conducted according to the C&CI Method in Fulton's Concrete Technology (Addis & Goodman, 2009). The two mix designs are summarised in Table 3-7 and Table 3-8, respectively, and the aspects considered during their design are detailed in the following subsections.

All mixes were mixed and prepared per the SANS 5861-1:2006 and SANS 5861-2:2006. Philippi dune sand and greywacke crusher sand consisted of a 50:50 percentage ratio by volume of both types of sand were adopted for this study.

As summarised earlier in this chapter, Table 3-4 provides a guideline for adopting recycled fine aggregates in this study. Under the source of the material, this study adopted industrial material, and in that way, the source was from an uncontrolled environment. That is an environment opposite to the standard laboratory conditions of temperature, relative humidity and aggressivity from atmospheric gases and ions.

The crushing process was done by a jaw crusher to obtain the fine material, and hence a single crushing process was utilized. The w/b was adopted without extra water addition, and no consideration for effective and apparent water content was considered. This technique was agreed upon to illustrate that recycled fine aggregates can be used directly for construction without being considered a lower property material.

Two w/b ratios of 0.45 and 0.60 were adopted for this research. The water content required for the design of cement content was calculated from the sand quality, as highlighted by Addis & Goodman (2009) in the Fulton Concrete's Technology book, chapter 11. As referred to in the chapter, Table 3-6 indicates the relationship between sand quality and the amount of water needed in a cubic meter of concrete (Addis & Goodman, 2009).

The typical water requirement for dune and crusher sand ranges from 170 l/m^3 to 200 l/m^3 (Walker & Alexander, 2013). The water content of 185 l/m^3 was adopted for this mix design which, as seen in Table 3-6, relates to an average of excellent sand quality. In addition, it permits the comparison of recycled concrete aggregate in the mix without any modifications.

Table 3-6: Water Requirement of concrete mixes (19mm stone, 75mm slump) adopted from (Addis & Goodman, 2009)

Sand Quality	**Water Content, l/m3**	
	Natural sand	Crusher sand
Very Poor	240	235
Poor	225	225
Average	210	215
Good	195	205
Excellent	180	195

3.4.1 Mix design A

In the first mix design, the 1 m^3 compliance of the concrete mix was not applied due to the consistent change in the coarse aggregate amount. The replacement of crusher sand with recycled fine aggregates was maintained at a 1 m^3 volume of concrete. According to the formula provided in the C & CI method summarised by Addis & Goodman (2009), coarse aggregates are continuously accustomed. The volume change in mix design A can be observed in bold highlights in Table 3-7.

3.4.2 Mix design B

In mix design B, the 1 m^3 compliance of a concrete mix was considered. The importance of ascertaining this volume was because it aimed to investigate only the recycled fine aggregates as the variable. The purpose of including both mix designs is to help understand the influence that replacement levels can impose on a metre cubic of a concrete mix. A scientific comparison cannot be effectively achieved without properly considering how the replacement material affects the main material. In order to analyse the influence of recycled fine aggregates in a concrete mix, all the other materials were kept constant per unit volume. Hence in Table 3-8, the amount of coarse aggregates in the mixture was maintained at 36.25% volume during the whole process as the replacement value of recycled fine aggregates varied by 0%, 25% and 50%. *(Equation 9*) illustrates the method used to achieve this design. The percentage of materials in a $1m^3$ of concrete was calculated as follows.

$$\% \, material = \left(\frac{Amount \ required \ in \ m^3}{Relative \ particle \ density \ of \ the \ material} \times 100 \right) \qquad \textit{(Equation 9)}$$

Table 3-7: Concrete mix design A

MIX DESIGN		**Control Mix = 50:50 Crusher and Dune**		**Mix B 25:25:50 RFA/Crusher/Dune**		**Mix C 50:50 Dune/RFA**	
Material (kg/m^3)	**Particle relative density**	**Mix 1 PC (w/b 0.45)**	**Mix 2 PC (w/b 0.6)**	**Mix 3 PC (w/b 0.45)**	**Mix 4 PC (w/b 0.6)**	**Mix 5 PC (w/b 0.45)**	**Mix 6 PC (w/b 0.6)**
Cement (CEM II-A L 52.5N)	3.14	411	308	411	308	411	308
Total Fine aggregate		863	951	831	918	800	886
Fine aggregate (Crusher sand)	2.72	432	476	207.8	230	0	0
Fine aggregate (Dune sand)	2.65	432	476	415.7	459	400	443
Fine aggregate (RFA)	2.58	0	0	207.8	230	400	443
Coarse aggregate (19-mm Greywacke)	**2.72**	**986**	**986**	**1007**	**1007**	**1028**	**1028**
Water (l/m^3)	1.0	185	185	185	185	185	185
w/b	-	0.45	0.60	0.45	0.60	0.45	0.60

Table 3-8: Concrete mix Design B

MIX DESIGN		**Control Mix = 50:50 Crusher and Dune**		**Mix B 25:25:50 RFA/Crusher/Dune**		**Mix C 50:50 Dune/RFA**	
Material (kg/m^3)	**Particle relative density**	**Mix 1**	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**	**Mix 6**
		PC (w/b 0.45)	**PC (w/b 0.6)**	**PC (w/b 0.45)**	**PC (w/b 0.6)**	**PC (w/b 0.45)**	**PC (w/b 0.6)**
Cement (CEM II-A L 52.5N)	3.14	411	308	411	308	411	308
Total Fine aggregate		863	951	782	876	811	864
Fine aggregate (Crusher sand)	2.72	432	476	201	225	0	0
Fine aggregate (Dune sand)	2.65	432	476	391	438	406	432
Fine aggregate (RFA)	2.58	0	0	190	213	406	432
Coarse aggregate (19-mm Greywacke)	**2.72**	**986**	**986**	**986**	**986**	**986**	**986**
Water (l/m^3)	1.0	185	185	185	185	185	185
w/b	-	0.45	0.60	0.45	0.60	0.45	0.60

3.5 Mixing and casting procedures

A total number of 26 concrete specimens were cast for one mix design. 24 concrete specimens of the 100 x 100 x100 mm cubes were cast for compressive strength tests, durability index tests, bulk diffusion, and accelerated carbonation test. A total of 156 concrete samples were cast considering the two water binder ratios and three replacement values adopted for this study.

After casting concrete into specified moulds, they were left to sit for 24 hours while covered with a plastic sheet to reduce the water evaporation rate. Demoulding was conducted afterwards, and curing began immediately as per SANS 5860 and SANS 5861-1, respectively. All concrete samples were cured in the water bath with respect to their testing ages.

3.6 Fresh properties of concrete

The workability of concrete was tested to investigate the fresh properties of concrete, using the slump test as per SANS 5862-1:2006. The slump test for each mix was conducted prior to casting the specimens to determine the discrepancies in the mix's uniformity. Before the slump test was conducted, a metal rod was dampened and then filled in three equal layers subjected to 25 blows from the tamping. During the test, moulds were slowly removed, and the slump was measured to the nearest 5 mm, that is, the distance between the inverted top mould and the highest point of the concrete, as illustrated in Figure 3-6. The test results were presented in terms of millimetres in depth.

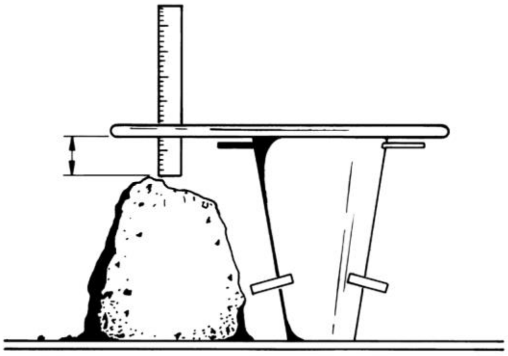


Figure 3-6: An illustration of the slump test reading

In this research, a compromise on lower slump depth was adopted to scientifically compare the replacement of recycled concrete aggregates in new concrete mixes. And as illustrated in Section 3.4, no additional water was included in the mix to adjust the slump readings.

a.) Control Mix 50:50

b.) 25% Replacement level mix 25:50:25

c.) 50% Replacement level mix 50:50

Figure 3-7: A picture of concrete slump tests performed for the study a.) Control Mix b.) 25% replacement of crusher sand with recycled concrete aggregates c.) 50% replacement of recycled aggregates.

3.7 Hardened properties of concrete

This section explains the experiments carried out on concrete after hardening. The hardened properties of concrete simulate the long-term behaviour of concrete mixes. These experiments investigated the suitability of the mix designs under environmental effects. A discussion of how the compressive strength test, the durability index tests, the accelerated carbonation test, and the bulk diffusion test were conducted are addressed in the following sections.

3.7.1 Compressive strength test

Three designated moulds of 100x100x100 mm were used for compressive strength testing after 3, 7, 28, and 112 days of curing. After every specified curing age, a total of three concrete cubes were removed from the water bath and tested for compressive strength. Prior to the compressive strength testing, the weight of the sample was measured, and four parallel dimensions were taken. A rate of 0.3 MPa per second of loading was adopted during the test. Compressive strength tests were conducted according to SANS 5863-2006.

3.8 Durability properties of concrete

Three short-term and two long-term tests were conducted to investigate the durability of concrete made with recycled fine aggregates. These tests consisted of the Oxygen Permeability Index test (OPI), water sorptivity index test (WSI), chloride conductivity index test (CCI), accelerated carbonation test and bulk diffusion test.

The following subsections explain in detail the procedure of the individual tests. All the tests were conducted according to SANS and the UCT Durability Manual, and where necessary other standards such as British and American standard was used.

3.8.1 Durability Index tests

Durability index tests measure the concrete's resistance to ingress of gases, liquids, and ions by establishing a trend on transport mechanisms such as permeability, conductivity, sorptivity and diffusion.

The OPI test is performed to determine the permeability of a concrete sample when exposed to a dropping pressure head; the CCI test gives a fast indicator of the conductivity of a concrete sample; and the WSI test tests the sorptivity and porosity of a concrete sample. Generally, these tests study the microstructure of the hardened concrete and their influence on the transport mechanisms, which are linked to their deterioration process.

The sample preparation for DI tests was conducted according to SANS 3001-CO3-1:2015, where a total of four 100 mm concrete cubes per mix were used. The samples were cured in a water bath for 28 days before coring and cutting into circular discs of 70 mm diameter and 30 mm thickness. From each cube, two discs were obtained and immediately after cutting, the discs were marked and pre-conditioned in the oven for seven days at 50°C before the durability tests. The following subsections provide in detail the procedures used to conduct the DI tests.

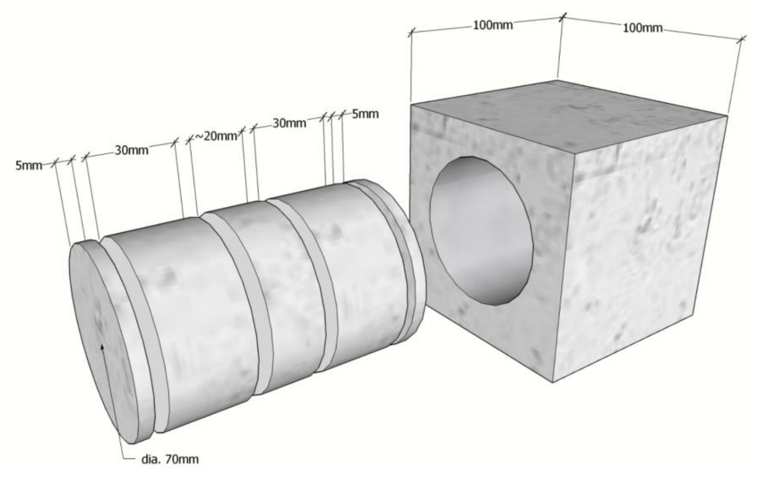


Figure 3-8: An illustration of how to obtain two discs from each 100 mm concrete cube, UCT DI Manual, (Alexander, 2017a)

3.8.1.1 Oxygen Permeability Index test (OPI)

An Oxygen Permeability Index test was performed according to the SANS 3001-CO3-2 (2015) and evaluated the overall microstructure of the concrete. The OPI test. The pressure decay of oxygen was recorded as it passes through a concrete disc of 68-70mm diameter and 30mm thickness over a falling head permeameter. The schematic diagram of the test procedure is illustrated in **Error! Reference source not found.**

The OPI value is an average of the negative logarithm of the coefficient of concrete permeability. The test gives a proper technique for assessing the state of compaction, the existence of voids and pathways, and the degree of interconnectivity of the pore system.

Four concrete discs were placed in the desiccator, conditioned at 23 ± 2°C for a minimum of 2 hours and a maximum of 4 hours. This step was done to cool their temperature from the oven conditions, i.e., 50°C. Each sample was then placed in its chamber, and pressure readings were recorded until the pressure dropped to 50 kPa or for 6 hrs, whichever came first, then the reading was stopped.

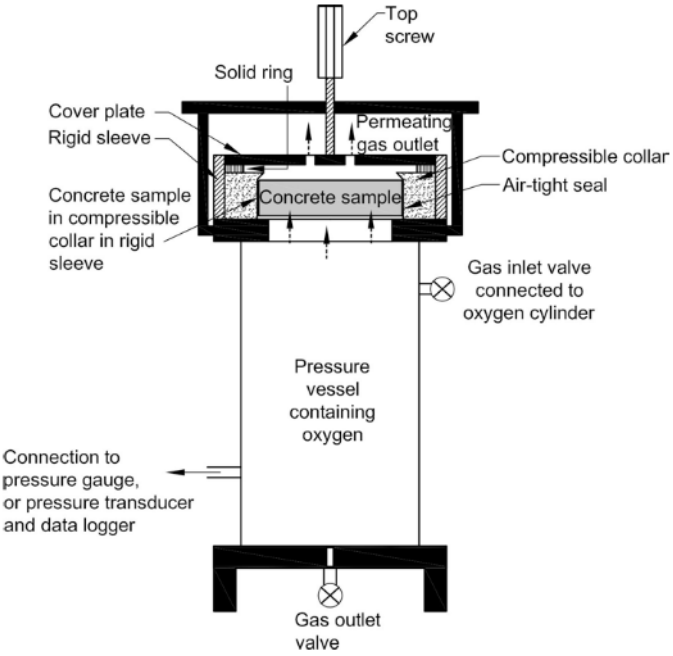


Figure 3-9: Schematic illustration of an oxygen permeameter(Alexander, 2017)

3.8.1.2 Water Sorptivity Index Test (WSI)

According to the UCT Durability Index Manual (DI) by Alexander (2017), the WSI test was carried out by calculating the absorption rate of calcium hydroxide solution through the porosity of the sample inside dry concrete discs under capillary action.

The samples from the OPI test were used because it is assumed that no additional drying is required after OPI testing since the samples are not exposed to any environment that can lead to moisture absorption. In achieving this, the samples were stored in a desiccator when not in use. The thickness and diameter of each sample were measured and recorded taken from 4 points equally spaced around the perimeter of the specimen. The curved sides near the marked surface were sealed with packaging tape to avoid solution penetration through the sides as part of the test preparation. After the samples were sealed, the dry mass was recorded.

A metal tray was used to conduct this test, as seen in Figure 3-10. Ten layers of paper towel were placed on it. Later on, the calcium hydroxide solution was poured into it. The solution was maintained above the paper towel, and bubbles were removed by straightening the paper towel from the centre towards the edges. The final water level was supposed to be slightly just above the bottom edge of the sample, as is illustrated in Figure 3-10.

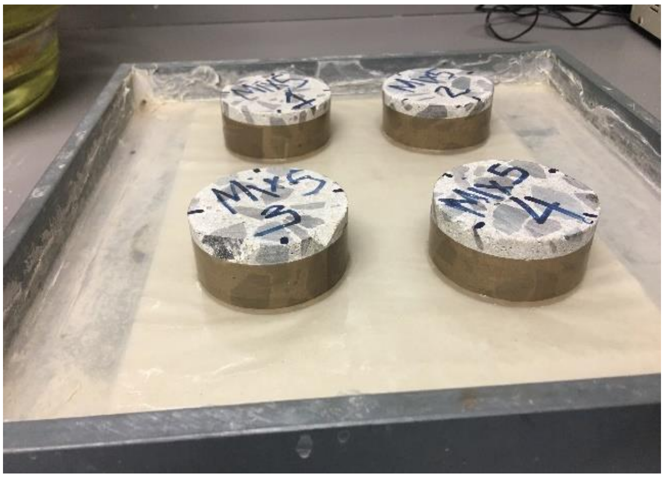


Figure 3-10: Test set up for the water sorptivity according to the DI Manual.

The samples were immediately placed on the metal tray with the test face downwards as the stopwatch started with an interval of 15 seconds for each. The samples were then weighed at 3, 5, 7, 9, 12, 16, 20 and 25 minutes. After removing each sample for weight measurement at the respective time intervals, care was taken on the exposed surface, being the saturated surface dried. The stopwatch was not stopped during the weight measurements.

After each sample was weighed and recorded, they were placed in a vacuum saturation tank with the tape left in place. The samples were placed on their curved and not flat sides to increase their exposed surface area. The tank was evacuated between -75 and -80kPa and maintained under vacuum for 3 hours ± 15 min. During the test, the vacuum pressure was not allowed to rise above -75kPa. After 3 hours ± 15 min, the calcium hydroxide solution was allowed to flow into the tank until the solution was 40mm above the samples.

Figure 3-11: Vacuum saturation tanks used for water sorptivity test

After the solution was allowed in the tank, the pressure was re-established between -75 and -80 kPa. This state was maintained for another 1-hour ± 15 min, and during this duration, the pressure was not allowed to rise above -75kPa. Afterwards, the air was allowed to enter the tank, and the vacuum was released. The samples were then allowed to soak in the solution for an additional 18 ± 1 hours. After 18 ± 1 hr of soaking, the samples were removed from the tank, and the dry surface condition resumed with a paper towel and weighed for vacuum saturated mass.

3.8.1.3 Chloride conductivity Index Test

The CCI test is performed according to the SANS 3001-CO3-3 (2015) for the CCI test. It is done to assess the resistance of the concrete samples to chloride penetration. The performance of these samples was correlated to the same concrete mix in a high chloride environment. In order to cool their temperature from the oven conditions, i.e., 50°C, four concrete discs were placed in the desiccator, conditioned at 23 ± 2°C for a minimum of 2 hours and a maximum of 4 hours.

Afterwards, each sample was weighed, the dry mass was recorded, and placed in a vacuum saturation tank. The samples were placed on their curved and not flat sides to increase their exposed surface area. The tank was evacuated between -75 and -80 kPa and maintained under vacuum for 3 hours ± 15 min. During the test, the vacuum pressure was not allowed to rise above -75 kPa. After 3 hours ± 15 min, the sodium chloride solution was allowed to flow into the tank until the solution was 40mm above the samples.

After the solution was allowed in the tank, the pressure was re-established between -75 and -80 kPa. This state was maintained for another 1-hour ± 15 min, and during this duration, pressure was not allowed to rise above -75 kPa. Afterwards, the air was allowed to enter the tank, and the vacuum was released. The samples were then allowed to soak in the solution for an additional 18 ± 1 hours. After 18 ± 1 hr of soaking, the samples were removed from the tank, and the dry surface condition resumed with a paper towel and weighed for vacuum saturated mass. For the next phase, all the testing procedures were to be completed within 15 min of removing a specimen from the sodium chloride (NaCl) solution.

The samples were then placed in a chloride conductivity cell filled with the 5M solution of sodium chloride. A DC power supply of 10V was introduced to initiate the chloride ions' movement in the cell. The conductivity was measured through the current passing through the concrete samples.

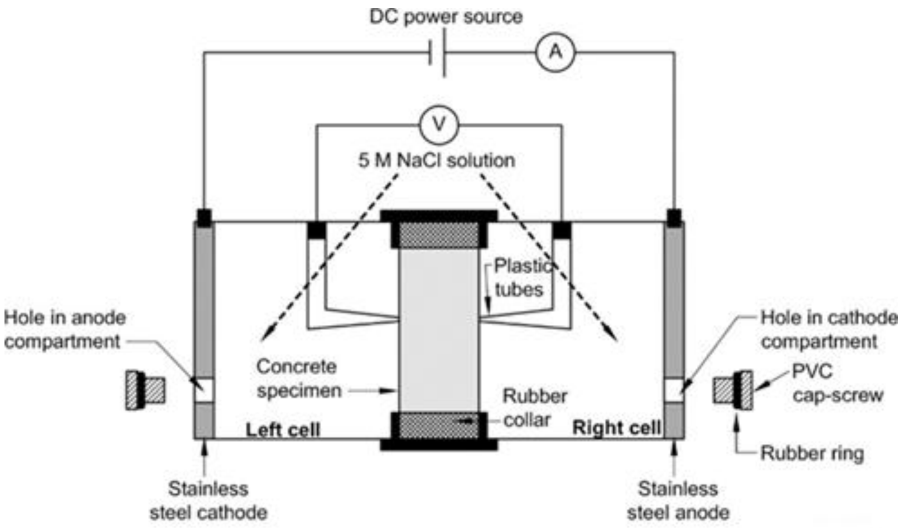


Figure 3-12: Test set up for chloride conductivity test (Alexander, 2017b).

3.8.2 Bulk Diffusion Test

The bulk diffusion test was conducted as per ASTM C1556 (2003). Four samples of 100x100x100 mm specimens per mix design were used for this test. After 28 days of curing, the samples were rinsed with water, scrubbed with a stiff nylon brush and airdried until no moisture could be removed from the surface with a dry paper. The exposure samples were surface-dry but internally moist before the epoxy coating. This condition was satisfied by standard moist curing of specimens allowed to air dry for not more than 24 hours in laboratory air maintained at 23 ± 2°C and 50 ± 3 RH. The samples were then epoxy coated without an initial slice cut out for initial chloride-ion content as the standard permitted extrapolation from the chloride profile equation.

All sides of the samples, except the finished surface, were left to allow the solution to enter. The initial mass of the samples was taken after the coating had hardened. The samples were immersed in a calcium hydroxide solution bath of approximately 3 g/L at 23 ± 2°C in a tightly closed plastic container. The solution was maintained above the samples to avoid the effect of carbonation. After 48 hours of immersion, the samples were removed from the container, and the mass was recorded. 48 hours of immersion was assumed to be sufficient to achieve a constant mass change.

The samples were then rinsed with water and immersed in the container, as illustrated in Figure 3-13, filled with sodium chloride solution (165 ± 1 g NaCl per L of solution). The container was then placed in an environmentally controlled room maintained at 23 ± 2°C and 50 ± 3% RH for 120 days. After 120 days, the samples were removed from the solution and rinsed with tap water. After the exposure time, the samples were left to dry in the environmental room for 48 days prior to cutting 6mm slices of each sample, cut from the exposure surface to the inner surface.

The samples were cut strategically to ensure that the last slice was not contaminated since it was used for initial chloride-ion content determination. About 8 slices were retrieved from each sample for testing. Two samples were used for one mix design. The slices were kept in the environmental room at 23 ± 2°C and 50 ± 3% RH for 24 hours to dry. After drying, the samples were crushed in the jaw crusher and pulverized into powdered samples stored in a tightly closed plastic bag to prevent contamination before titration analysis.

Figure 3-13: Samples immersed in sodium chloride solution for the bulk diffusion test

3.8.3 Accelerated Carbonation test

This test was conducted to study the effects of carbonation on concrete made with various levels of recycled concrete aggregates at two different water binder ratios. After 28 days of curing, three 100 mm concrete cubes were removed from the bath and placed in an environmental room at 45 ± 2.5 % RH and 23 ± 3 ℃. The concrete samples were then positioned on top of four cubical edges to expose all sides of the samples to dry for a period of 60 days.

Salvoldi (2010) indicated that on a fully saturated concrete, no CO_2 penetration could occur. Hence, the concrete samples need to be pre-conditioned to achieve the internal Relative Humidity (RH) of about 70 – 65%. According to the prediction model illustrated in Figure 3-14, the pre-conditioning can be achieved if the samples are stored in the environmental room set at 23 ± 3 ℃ and 45 ± 2.5 % RH for 60 days (Salvoldi, 2010). The samples' drying rate would not influence the accelerated carbonation rate at this age. However, the prediction model adopted by Salvoldi (2010) did not consider the effect of the water binder ratio or different types of binders. Hence, the mass change of the concrete samples was recorded every week until the mass loss of less than 0.005 kg per week was observed, i.e., 0.3% of the original mass of the sample).

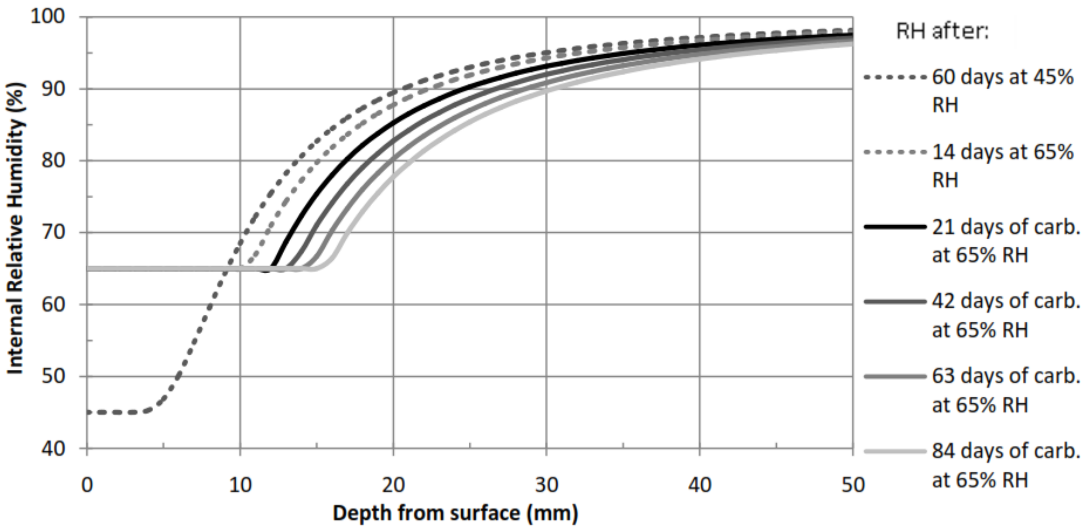


Figure 3-14: The effect of internal relative humidity against the depth of the sample during various drying and carbonation cycles (Salvoldi, 2010)

After 60 days of pre-conditioning, the samples were epoxy coated on four parallel sides except for two opposite sides left unsealed to allow a two-directional means of carbonation front progression. The coated samples were then moved into the carbonation chamber without any carbon dioxide released for 14 days at a controlled internal environment of 65 ± 5% RH and temperature of 20 ± 2℃. Subsequently, carbon dioxide was released at a concentration of 2 ± 0.1% after the 14 days under the same conditions, and carbonation depth was measured at 4, 8 and 12 weeks. The carbon dioxide gas concentration was maintained at 2% under this controlled environment. The carbonation process was a comparatively slow phenomenon to attain measurable results under the samples' specified time.

After the samples had reached four weeks of exposure, a 20 mm thick slice was cut, and the freshly cut surface was sprayed with a solution of phenolphthalein. A repetitive procedure for spraying the samples was done after 24 hours. The carbonated depths on the concrete surface were measured perpendicularly to the exposure face at six different points on the samples. Later on, an average carbonation depth could be determined and concluded. After recording the carbonation depth, the samples were resealed with epoxy and taken back to the carbonation chamber for further carbonation.

3.9 Summary of the test methods

This chapter comprised of five test summaries; the introduction comprised materials used, their properties, and extraction methods. The second section consists of test methods and their experimental procedure. The third section summarises the adopted concrete mix design framework and calculations for mix designs A and B. Section four consists of fresh concrete properties on the workability of the concrete. Sections five and six explain a summary of investigations on the hardened concrete properties using compressive strength, normal drying shrinkage, durability index tests, bulk diffusion tests and accelerated carbonation tests.

4 Results and Analysis

4.1 Introduction

This chapter summarises the results and provides an analysis of the experimental methods conducted for this research, as illustrated in Chapter 3. This chapter aims to highlight the link between the hypothesis provided in Chapter 1 and the reasoning for the gaps illustrated in the literature review chapter.

The first section reports on material characterisation tests conducted for this research. This section consists of the results and analysis of the particle size distribution of fine aggregates and their relative densities. Section two consists of a summary of results from investigating concrete fresh and mechanical properties. This section summarises the results and analysis of the slump test and compressive strength test of the mixes. Section three consists of a summary of results from testing the durability properties of concrete. Under this section, a summary of the results of the Durability Index test, accelerated carbonation tests, and bulk diffusion tests. Section four and five consists of the chapter's conclusion and chapter summary.

4.2 Characterisation of materials

4.2.1 Particle size distribution analysis of the fine aggregates

Test results for both individual fine aggregates and the combination of fine aggregates used for the mix design are shown in Table 4-1 and Table 4-2, respectively. The gradation of all three individual fine aggregates and their respective combinations within the various mix designs are illustrated in Figure 4-1 and Figure 4-2. The procedure for undertaking this test was conducted as described in Section 3.3.

At least 90% of all three individual fine aggregates – dune sand, crusher sand and FRA, passed through a sieve with square apertures of nominal size 4,75 mm and was retained on the sieve with square apertures of nominal size 75µm as seen in Figure 4-1 and Table 4-1. At least 97% of dune sand passed through the 1.18 mm standard sieve and is retained on the 150 µm standard sieve. Therefore, dune sand can be regarded as a single-sized graded aggregate owing to the sorting power of the wind (Grieve, 2009). About 90% of crusher sand passed through a 4,75 mm sieve and was retained on the 75µm sieve. However, both the dune sand and crusher sand individually do not comply with the SANS 3001: AG1 or ASTM 33 standard limits of the gradation curve, as can be observed in Figure 4-1. Hence, as mentioned in chapter 2, the combination of both dune sand and crusher sand provides an adequate blend of continuous particle size and shape to be utilised for concrete applications as illustrated in Figure 4-2. As summarised by Walker & Alexander (2013), particle size distribution offers an effective method of analysing the performance of the source of aggregates when used in concrete.

Table 4-1: A summary of the percentage passing of the individual fine aggregates adopted for this study.

Sieve No.	**Percentage passing on the standard sieve sizes**		
	Recycled fine aggregates	**Crusher sand**	**Dune sand**
4.75	100.0	89.8	100.0
2.36	82.5	50.7	100.0
1.18	63.5	30.4	97.4
0.6	46.5	19.7	56.8
0.3	29.0	12.8	31.8
0.15	18.0	7.7	5.6
0.075	8.0	2.0	1.2
0.01	0.0	0.2	0.7

Table 4-2: A summary of the percentage passing of the combination of fine aggregates adopted for this study.

Sieve No.	**Percentage Passing on the standard sieve sizes**		
	0% RFA	**25% RFA**	**50% RFA**
4.75	94.89	97.45	100.00
2.36	75.37	83.31	91.25
1.18	63.91	72.17	80.44
0.6	38.23	44.93	51.64
0.3	22.29	26.33	30.38
0.15	6.67	9.24	11.82
0.075	1.59	3.09	4.59
0.01	0.42	0.38	0.34

For recycled fine aggregates, it should be noted that the jaw crusher, as seen in Figure 3-3, was set at a standard aperture of 5 mm to produce fine aggregates conforming to SANS 201 standard sizes, as shown in Table 4-1 and Table 4-2.

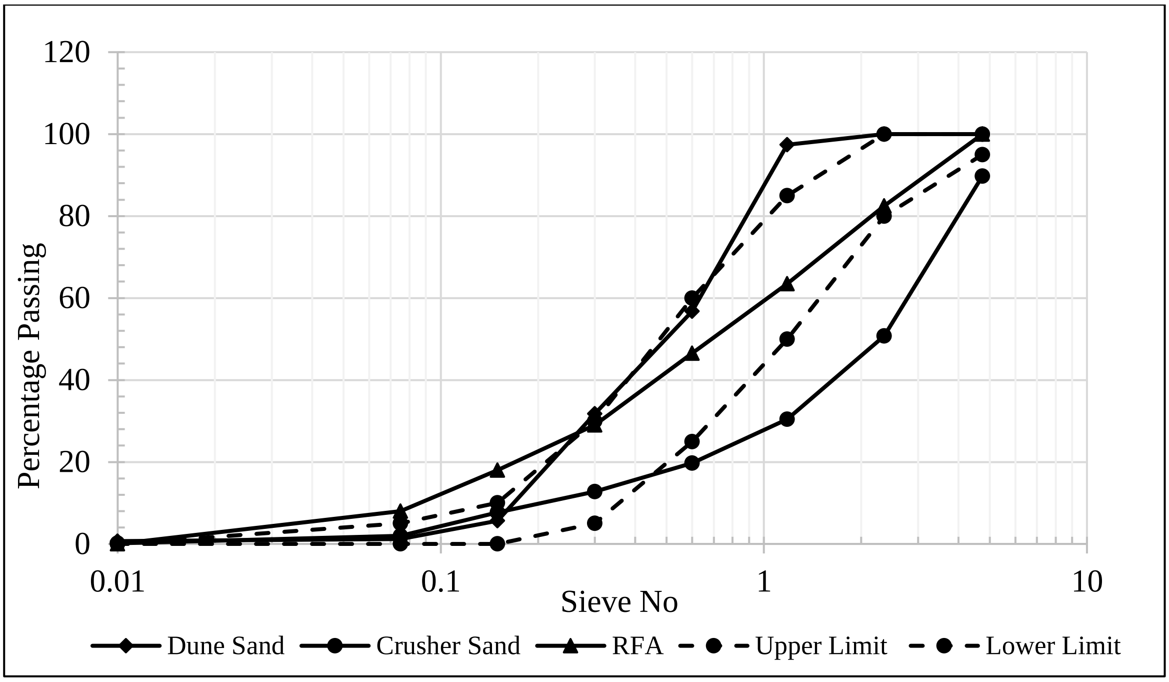


Figure 4-1: Particle size distribution of individual fine aggregates used in the research.

As seen in Figure 4-1, and as a result of setting a single aperture size on the jaw crusher, all aggregates passed through sieve no. 4,75 mm and was retained in the pan. Additionally, it was summarised by (Evangelista et al., 2015) that, although the amount of fines produced depends on the jaw crusher's aperture after crushing, the particle size distribution does not depend on the jaw crusher's aperture, and these results were in similar agreement with fineness modulus values.

At the 0.075mm sieve size, the percentage passing for recycled fine aggregate, crusher and dune sand was measured to be 8%, 2% and 1.2%, respectively. As compared to the crusher and dune sand distribution, it was measured that recycled fine aggregates had the highest percentages of finer materials retained on the 0.075 mm sieve.

This observation concedes with the hypothesis of this study that reports on the presence of adhered cement paste at the surface of recycled fine aggregates. These results show that about 4 to 6 times the amount retained for the crusher sand and dune will be retained for the recycled fine aggregates in their respective sieve. It is also observed that the increase of recycled fine aggregates across the different combinations has increased the amount of fine particles retained on the 0.075 mm sieve, and, similarly, the uniformity in the particle size distribution of the aggregates across the sieve sizes as observed in Figure 4-1 and

Table 4-2.

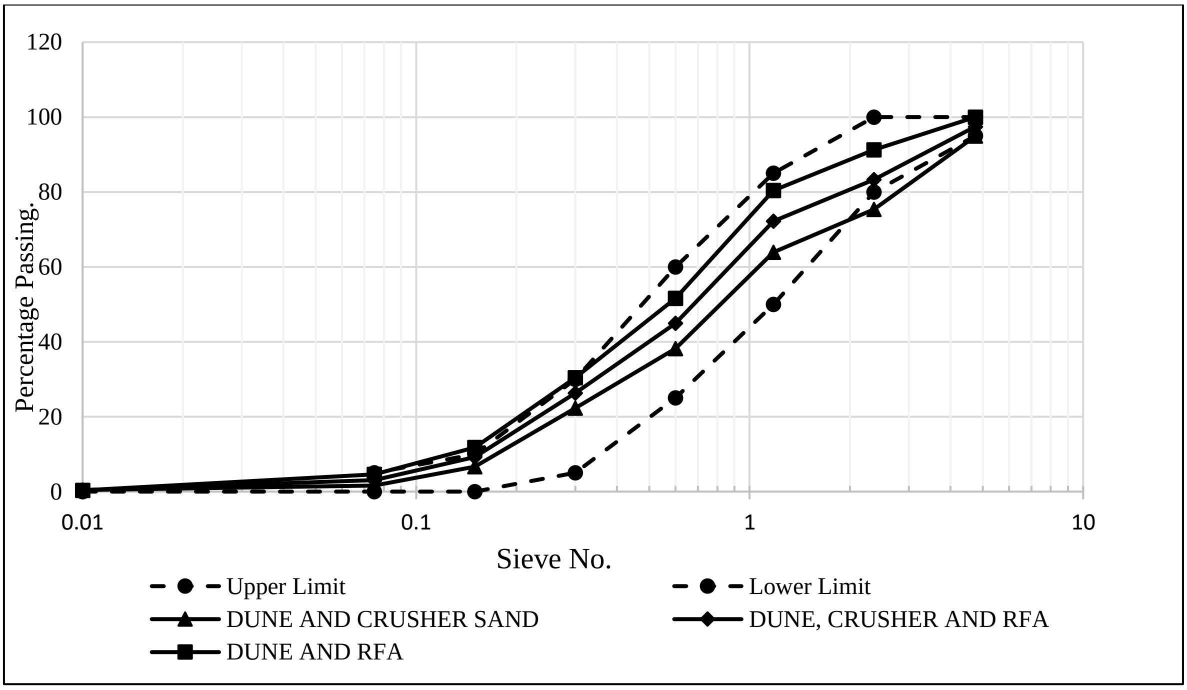


Figure 4-2: Particle size distribution of the combined fine aggregates used in the research.

Hence, it can be inferred that the crushing process produces a relatively larger amount of fines than a crusher and dune sand. Furthermore, the adhered cement paste from the recycled fine aggregates gets pulverised during the crushing process, leading to higher fine contents in recycled fine aggregates compared to crusher and dune sand (Evangelista et al., 2015).

These results also agree with those of Evangelista et al. (2015). They concluded that a significant amount of fines is present on the surface of coarse and fine recycled aggregates, resulting from the crushing process. These results agree with González-Taboada et al. (2016), who reported that the grading of recycled concrete aggregate is comparable to that of natural aggregate; however, because of the attached mortar on the surface of the aggregates, recycled sand generally has finer particles content than the natural fine aggregate. The replacement of RFA at both levels complied with the grading limits specified in ASTM 33, as seen in Figure 4-2.

Further discussion on the combination of fine aggregates adopted for the mix designs is summarised in

Table 4-2 and Figure 4-2 with compliance to the standard size for fine aggregates. Similarly, the distribution of the aggregates across the combinations shows the increase of the materials passing through the respective sieve size by a factor of 2 as the replacement value of recycled fine aggregates increases from 25% to 50% as compared to the 0% replacement value of the recycled fine aggregates.

As illustrated in Figure 4-2, all the three combinations of fine aggregates used in the research are within the grading envelop of ASTM C33-93. This grading envelope was done to eliminate the influence of different fine aggregate grading on the result of the study.

Since particle size distribution analysis is done in conjunction with the fineness modulus of the aggregates as stipulated in the ASTM Designation: C33-93, the fineness modulus of these aggregates was calculated from the sieve analysis results.

The fineness modulus of aggregates assists in estimating the proportions of fine aggregates during the mix design stage of concrete. It indicates the coarseness or fineness of the aggregates. The lower the fineness modulus of the aggregates, the higher the amount of paste required in the concrete mix, and therefore, the higher the water demand. In principle, particle size distribution with the same fineness modulus will require the same amount of water to form a concrete mix of the same consistency. ASTM Designation: C33-93 specifies that fine aggregate shall have not more than 45% passing any sieve and retained on the next consecutive sieve sizes, and its fineness modulus shall be not less than 2.3 nor more than 3.1.

Research has shown that a change in the fineness of sand affects the workability of concrete mixes. Hence, to determine the optimal fineness modulus of fine aggregates, a suitable grading of aggregate blends must be determined that is acceptable and cost-effective. The most optimum concrete mix is produced by aggregates with a smooth and distributed grading curve (Kosmatka & Wilson, 2011).

Additionally, incorrect aggregate combinations affect the water to cement ratio, workability, compatibility, and cohesion qualities of the concrete mixes. A mix with very fine sand becomes less economical since it requires a higher amount of cement, while a mix with coarser sands would be more economical however produce mixes with less cohesion and are unworkable (Kosmatka & Wilson, 2011). The fineness modulus was calculated from the three individual aggregates and summarised in Table 4-3.

Table 4-3: Fineness modulus of individual fine aggregates used in this research.

Material property	Type of sand	Average, Value	Influence on concrete properties	Blends of aggregates	Average, Value
Fineness Modulus	Crusher sand	3.79	Less economical but harsher mixes	Dune and crusher sand	2.9
	Dune sand	2.10	More economical and easy to work with mixes	Dune, crusher sand and RFA	2.1
	Recycled fine aggregates	2.57	Moderate costs with optimum workability of mixes	Dune and RFA	2.4

It can be observed from the results that the fineness modulus of 0% and 50% replacement blends fall within the standard requirements except for the 25% replacement of fine aggregates. This measurement can be seen from the lowest slump value of 20 mm achieved during the workability mixes of lower w/b ratios. However, higher slump values of 65 mm were achieved during the higher w/b ratios of the same combination of aggregates, making the concrete mixes more workable.

4.2.2 Particle relative density

The particle relative density of the crusher sand was found to be higher than that of dune sand and recycled fine aggregates. However, as seen in Table 4-4, the differences in values were very minimal in comparison to dune sand and recycled fine aggregates, respectively. Recycled fine aggregates showed the lowest value as expected due to the comparatively low density of the old mortar bound to the natural aggregate's grains.

Similar observations were made by Evangelista et al. (2015); Mardani-Aghabaglou, Tuyan & Ramyar (2015); Kumar, Gurram & Minocha (2017); Meddah, Al-Harthy & Ismail (2020) work on recycled concrete aggregates having lower relative density than the corresponding natural aggregates used in their studies. This decrease is caused by adhered mortar present on the surface of recycled fine aggregates (Ridzuan et al., 2005; González-Taboada et al., 2016).

Table 4-4: Particle relative density of individual fine aggregates used in the research

Physical properties	Type of sand	Value
Particle relative density	Crusher sand	2.72
	Dune sand	2.65
	Recycled fine aggregates	2.58

4.3 Fresh concrete properties

4.3.1 Workability

A slump test was conducted on all mixes during the workability investigation prior to casting the concrete into moulds. The highest slump values were observed in the 0.6 w/b ratio compared to the 0.45 w/b ratio, as seen in Figure 4-3.

This trend was expected since the same amount of water content was used for both low and high w/b ratio mixes. Hence, the higher w/b ratio mixes exhibited more workability than the lower w/b ratio mixes.

It was observed that although the 0.45 w/b ratio mixes showed lower slump values, however, these mixes were still workable as they were relatively easy to vibrate into moulds mechanically. No segregation of the concrete mixes was visibly observed through the slump test, as the mix exhibited cohesiveness and a lack of spreading within the mass of concrete.

Studies have shown that concrete with a higher replacement level of RFA exhibits lower slump values than concrete with natural aggregates due to the high amount of adhered cement paste found on the surface of recycled fine aggregates (James Mackechnie & Munn, 2011; Dimitriou, Savva & Petrou, 2018; Thomas, Thaickavil & Wilson, 2018). For concrete with RFA, a decrease of about 5-20% of the slump value is reported compared to concrete with natural aggregates. It is concluded that RFA increases the internal friction within the concrete matrix due to the adhered mortar. And therefore, workability was expected to decrease as the replacement level of RFA increased (Kumar, Gurram & Minocha, 2017).

The highest slump value was recorded for the 0.45 w/b ratio at the 0% replacement of recycled fine aggregates mix. The lowest slump value was recorded at the 25% replacement value for the recycled fine aggregates mix, as seen in Figure 4-3. The difference between the two replacement level mixes results were attributed to the higher amount of fines in the later mix. These results were due to the addition of recycled fine aggregates, as seen from the fineness modulus results in Table 4-3. Contradictory to the expected values, the 50% replacement mix showed an adequate slump value compared to the 25% replacement mix, which can also be inferred from the moderate fineness modulus of the blend. The blend at 50% replacement level had finer particles only from RFA as compared to the higher amount of finer particles present at the 25% replacement blend, which had finer particles from the RFA and the crusher sand.

For the 0.6 w/b ratio, the highest slump value was recorded at the 0% replacement of the RFA mix, similar to the 0.45 w/b ratio. However, contrastingly to the 0.45 w/b ratio mix, the lowest slump value was recorded at the 50% replacement value for the recycled fine aggregates mix, as seen in Figure 4-3. These results were consistent with the expected trend since the increase in RFA decreases the water content in the mix due to the attached cement paste.

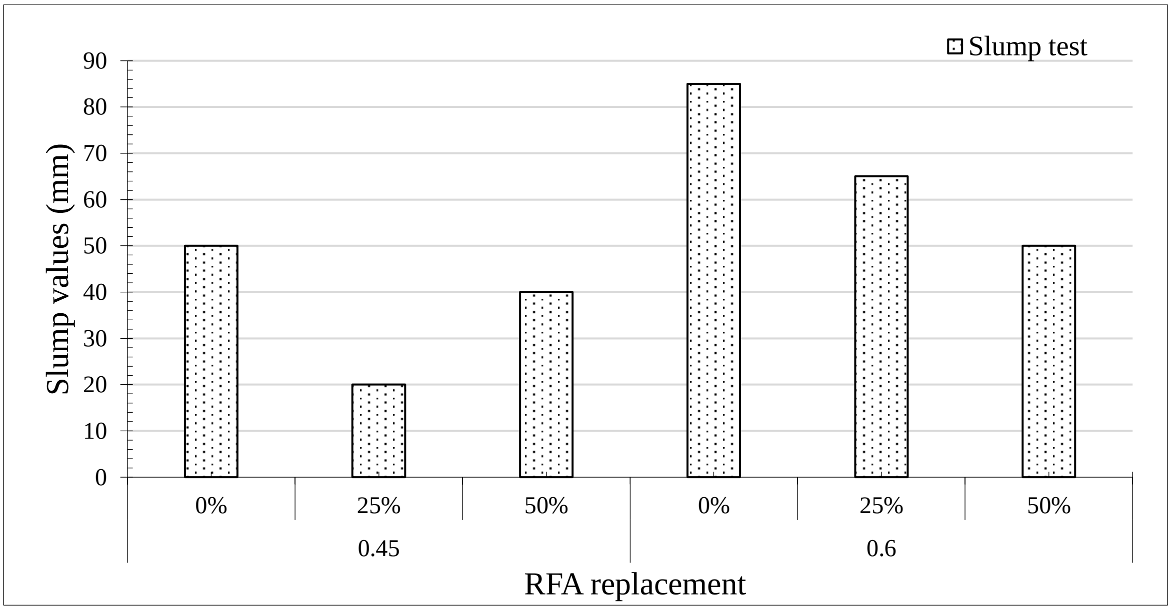


Figure 4-3: A summary of slump results for concrete mixes with two w/b ratios and three replacement levels of RFA

Generally, these values show that adding recycled fine aggregates decreases the workability of concrete (Kumar, Gurram & Minocha, 2017). Depending on the fine aggregate combination used, these values show a decrease of 60% of the slump value for the 25% replacement level of the recycled fine aggregates compared to the control mix slump value for the 0.45 w/b ratio mixes. Although for this same replacement value, only about a 23% decrease in the slump value was observed for the 0.6 w/b ratio mix. For the 50% replacement level of RFA, a decrease of 20% of the slump value is observed from the control mix for mixes with a 0.45 w/b ratio. And a decrease of 41% is observed from the control mix for the 0.6 w/b ratio mixes.

Mixes with a lower w/b ratio have low workability compared to higher w/b ratio owing to the main provision of enough water for cement hydration but little to no water present in the fresh concrete state for inter-particle lubrication.

During the workability test, it can be seen through the reduction of slump values that the properties of RFA significantly influence the behaviour of fresh concrete made with RFA. Lower slump values are observed in mixes with RFA replacement which illustrates less water for inter-particle lubrication or workability in the mixes.

It should also be noted that although the properties of recycled fine aggregates significantly affect the fresh properties of concrete, the mechanical properties showed slightly better to no influence on concrete made with RFA (Thomas et al., 2013).

4.4 Mechanical properties of concrete

The following section summarises the experimental results obtained from tests on the mechanical performance of hardened concrete made with recycled aggregates as a partial replacement for natural fine aggregates.

4.4.1 Compressive strength test results

This section summarises the compressive strength test results conducted for the study at various curing ages. Generally, mixes with lower water binder ratios (w/b = 0.45) indicated higher compressive strength values than mixes with higher water binder ratios (w/b = 0.6). These results were attributed to the concrete's lower porosity and denser microstructure in lower w/b ratio mixes compared to the higher w/b ratio mixes.

Compressive strength results indicated that the addition of unmodified recycled fine aggregates positively and, in most cases, neutrally affected the concrete's compressive strength. For the 0.45 w/b ratio mixes, the compressive strength results, as seen in Figure 4-4, indicated that for mixes with RFA, slightly higher or comparable values were observed compared to concrete without RFA at all testing ages. At 25% replacement levels of RFA, slightly higher values were observed than at 50% replacement level of RFA. And for all curing ages except at 28 days, the compressive strength of 25% and 50% replacement level of RFA was slightly higher or comparable to the mixes without RFA, respectively. These results show that aside from the low strength concrete design, illustrated by a 0.6 w/b ratio, even the 50% replacement level of RFA at a 0.45% w/b ratio can achieve comparable compressive strength results from concrete without RFA.

Similar to the 0.45 w/b ratio mixes, the 0.6 w/b ratio mixes also indicated that mixes with RFA had a slightly higher or comparable compressive strength result to concrete without RFA. Generally, higher compressive strength values of an average of 6% were observed for the 25% RFA replacement level mixes compared to the mixes with 0% and 50% replacement level of RFA. In Figure 4-5, it is observed that compressive strength for mixes without RFA increases gradually in compressive strength compared to mixes with RFA. The compressive strength gain for mixes with RFA shows stagnation during early ages and higher compressive strength values at older/mature ages. This non-uniformity in mixes with RFA can be explained through the slow progression of continuous hydration caused by water release at a later age, a phenomenon reported by González-Taboada et al. (2016). Additionally, the lowest compressive strength values were recorded at 3 and 7 days for the 50% replacement level mixes and an increase in the values was only observed after the 28 days of curing age which further explains the concept of continuous hydration. This observation is not seen in the 0.45 w/b ratio, where all the results show lower values at the 0% replacement level mixes compared to the 25% and 50% replacement level mixes.

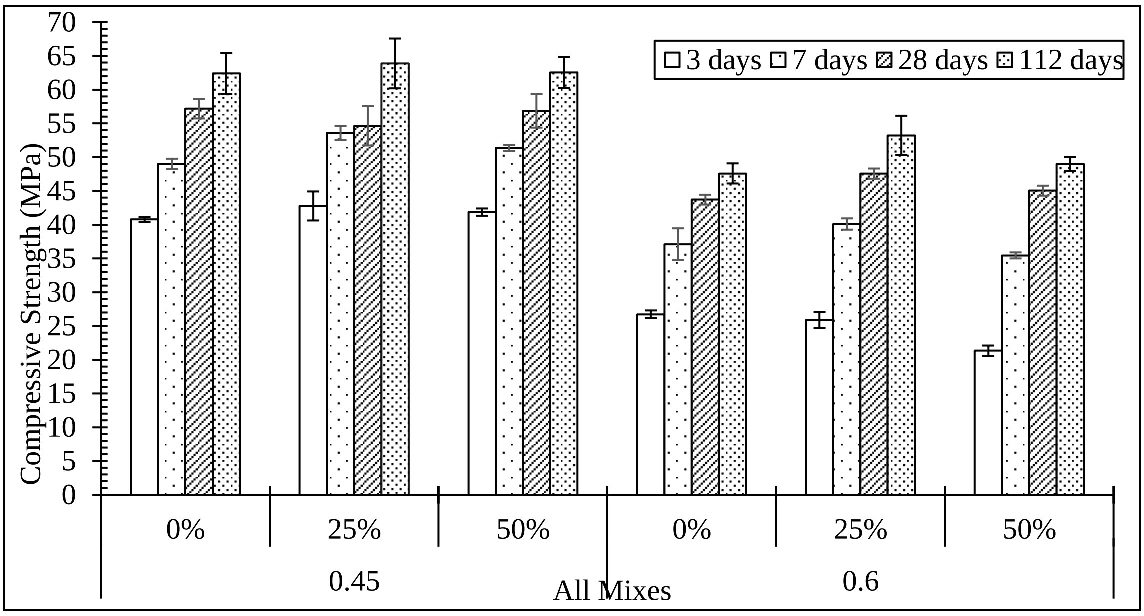


Figure 4-4: A summary of the compressive strength results for the two w/b ratios and three replacement levels of the recycled fine aggregates (RFA).

The same results were analysed using curing ages to illustrate the influence of recycled fine aggregates addition on strength gain. Figure 4-5 illustrates the increase in strength age-wise from 3, 7, 28 and 112 days.

At 3 days, the highest compressive strength value is observed at a 25% replacement level of RFA for mixes with a 0.45 w/b ratio, but for mixes with 0.6 w/b ratios, the highest strength is observed at a 0% replacement level of RFA. At 7 days, the highest compressive strength value is observed at a 25% replacement level for both w/b ratios. These results illustrate that early compressive strength can be attained at a 25% replacement level of RFA.

At 28 days, mixes without RFA showed only a slightly higher compressive strength value than mixes with 25% and 50% replacement levels of RFA for the 0.45 w/b ratio. However, for the 0.6 w/b ratio, the 25% replacement level of RFA mixes showed a higher overall compressive strength value similar to 7 days mixes. These results illustrate that similar compressive strength values can be attained at the standard testing age for mixes with RFA replacement.

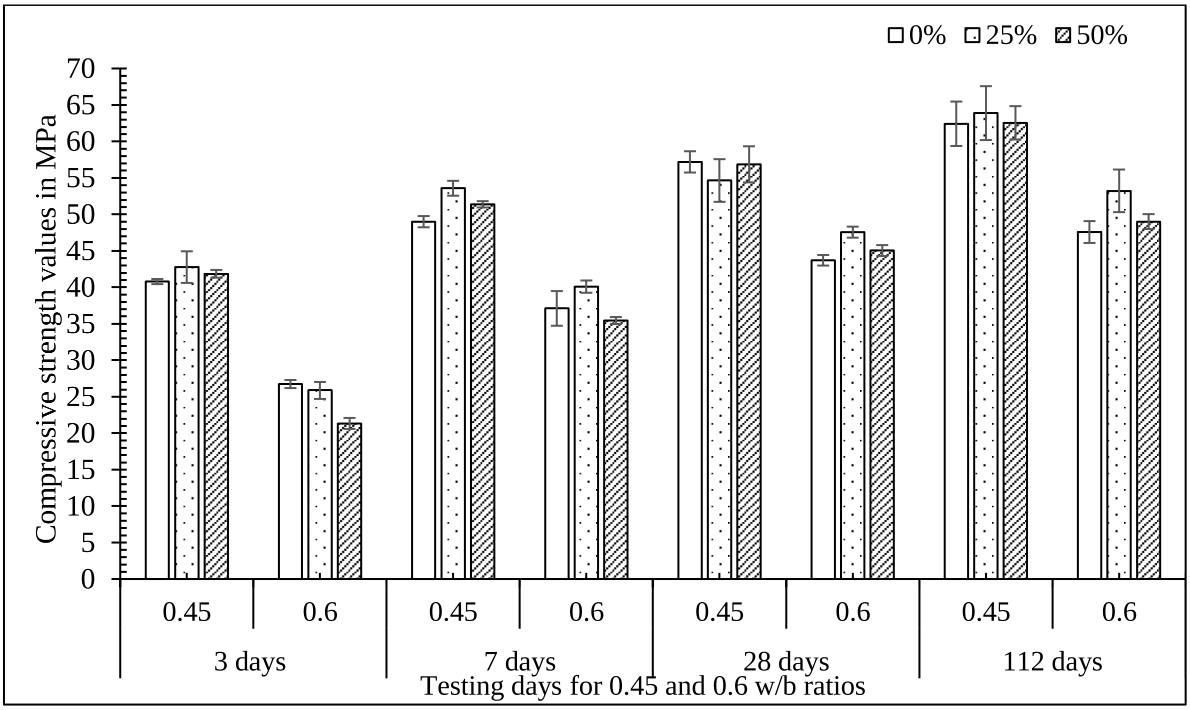


Figure 4-5: A summary of the compressive strength results from early to late ages at different replacement levels and two w/b ratios of the recycled fine aggregates (RFA)

At 112 days, mixes with a 25% replacement level showed higher compressive strength values than mixes without RFA and at 50% replacement level of RFA for both w/b ratios. It can be seen that although mixes without RFA showed the highest compressive strength values compared to other mixes at 3 days, strength values at 7, 28 and 112 days showed the highest compressive strength value mixes with 25% replacement of RFA as indicated in Figure 4-4. This increase in strength illustrates that the replacement of NA with RFA at 25% influences the strength of the mixes positively.

These results indicate that compressive strength improves with age because sufficient moisture is available to continue the cementing reactions. For the 0.45 w/b ratio, the control mix indicates concrete gains strength with time at an ever-decreasing rate. Although, the highest increase in compressive strength is observed during the first 7 days of curing. This ever-decreasing rate is illustrated at 3, 7, 28 and 112 days of 16.73%, 14.33% and 8.33%, respectively, across the ages. It was observed that concrete mixes with 25% replacement of RFA indicated a minimal increase in strength at 28 days compared to mixes with 0% and 50% replacement levels of RFA. However, at later ages of 112 days, mixes with 25% replacement levels of RFA show a strength increase of almost twice that of mixes with 0% and 50% replacement levels of RFA. These values are summarised in Table 4-5.

The highest increase was observed at the 25% than 50% replacement levels of recycled fine aggregates even after 112 days. Hence, RFA mixes with a higher w/b ratio only attain higher compressive strength at a later age compared to RFA mixes with a low w/b ratio.

Table 4-5: A summary of the percentage increase in compressive strength across curing ages for 0.45 w/b ratio mixes

	Replacement level (percentage increase), in %		
Age	**0%**	**25%**	**50%**
3 - 7 days	20	25	23
7 - 28 days	16	2	11
28 - 112 days	9	17	10

Similar to the 0.45 w/b ratio mixes, the highest strength increase was observed in the first 7 days of curing for the 0.6 w/b ratio mixes. Furthermore, the highest increase was observed at the 50% replacement level of RFA than 25% and 0% replacement of RFA during the early ages. However, after 112 days, the 25% replacement level of RFA showed the highest strength increase compared to 0% and 50% replacement levels of RFA.

Hence, it is observed that although RFA mixes with a higher w/b ratio are reported to have lower compressive strength values compared to low w/b ratio mixes, their percentage of strength increase is higher than low w/b ratio mixes.

Table 4-6: A summary of the increase in compressive strength across curing ages for 0.6 w/b ratio mixes

	Replacement level (percentage increase), in %		
Age	**0%**	**25%**	**50%**
3 - 7 days	39	55	67
7 - 28 days	18	19	27
28 - 112 days	9	12	9

As discussed in the literature review, most reported work on the use of RFA adopted a modification technique in order to compensate for the high porosity of the RFA. And as earlier discussed, it was advised against modifications in this study to eliminate the possibility of the modification being the cause for improved or harsher concrete properties instead of solely adding RFA.

Nonetheless, for the purpose of analysis work, these results contrasted those of most authors such as (Limbachiya, Leelawat & Dhir, 2000; Oikonomou, 2005; Yang, Chung & Ashour, 2008; Evangelista & de Brito, 2010; Zega & Di Maio, 2011; McNeil & Kang, 2013; Kumar, Gurram & Minocha, 2017) as discussed in the literature review.

These results also correspond to some scholars who reported an increase in compressive strength for mixes with partial replacement of RFA such as (Zega & Di Maio, 2011; Pereira, Evangelista & De Brito, 2012; Li, Xiao & Zhu, 2016; Kumar, Gurram & Minocha, 2017; Pedro, de Brito & Evangelista, 2017; Kirthika & Singh, 2020; Nedeljković et al., 2021).

Thomas et al. (2013) reported that recycled concrete's mechanical properties, i.e., compressive strength, are higher in lower w/b ratios than conventional concrete. The study concludes that the reduced w/b ratio lowers the discrepancies since the most crucial component is the limited porosity of the new cement paste.

Furthermore, these results were similar to those of González-Taboada et al. (2016); and Kumar, Gurram & Minocha (2017), that reasoned that the hydration process progresses with the replacement of RFA. (Kumar, Gurram & Minocha, 2017) also reported that mixes with up to 50% replacement levels of RFA had no significant deviation in compressive strength from the control mixes. Since the aggregate can store more water, this water can be released into the new mortar over time to continue to feed the cement for a longer time, which improves strength. (González-Taboada et al., 2016) also reported that when there is a high-water absorption in recycled concrete aggregates, a high amount of free water can be retained as moisture in the concrete mixes. This moisture can later be released into the binder matrix to provide a secondary reaction that improves or boosts the long-term compressive strength.

In addition, Pereira, Evangelista & De Brito (2012) concluded that similar compressive strength values were obtained for concrete made with recycled fine aggregates at both 30% and 50% replacement levels of RFA without the use of superplasticizers. Although some modifications were done by Zega & Di Maio (2011), the study also illustrated similar compressive strength values of mixes with 20% and 30% replacement levels compared to concrete without RFA.

Conclusively, whilst most research work on mechanical properties has concentrated on modifying the use of RFA due to their high-water absorption causing lower workability in the mix, this study has shown that RFA can be utilized without modifications and provide similar properties to those of conventional concrete. It should be noted that these results are owed to the use of a known high-quality source of C&DW, and therefore using a lower quality source of C&DW might measure lower compressive strength values.

4.5 Durability properties of concrete made with recycled fine aggregates.

4.5.1 Durability Index test results

This section summarises the experimental results that address the resistance of the concrete to environmental attacks caused by chloride ingress and carbonation. Additionally, the durability index (DI) tests were used to evaluate the durability properties of recycled concrete. Three durability index tests, oxygen permeability index, water sorptivity index, and chloride conductivity index, were used to compare the results between concrete with and without recycled concrete aggregates at three replacement levels and two w/b ratios. All DI results were discussed according to the criteria provided by Alexander, Mackechnie & Ballim (1999), as summarised in Table 4-7, which indicates the quality of concrete in the mixes.

Table 4-7: A guide to use for indicating the quality of concrete from durability index results by Alexander, Mackechnie, Ballim, 1999

Quality of concrete	Oxygen Permeability Index (OPI) log scale	Water sorptivity Index (WSI) mm/h$^{0.5}$	Chloride conductivity Index (CCI) mS/ cm
Excellent	>10.0	< 6	< 0.75
Good	9.5 - 10	6 - 10	0.75 - 1.50
Poor	9- 9.5	10 - 15	1.50 - 2.50
Very poor	< 9	> 15	> 2.50

4.5.1.1 Oxygen Permeability Index test results

According to the criteria adopted for concrete durability tests, the Oxygen Permeability Index (OPI) results are calculated as the negative log of samples' Darcy coefficient of permeability (k). Despite having different replacement values of RFA, all mixes showed an excellent quality of concrete, as seen in Figure 4-6.

For the 0.45 w/b ratio mixes, both 0% and 25% replacement mixes showed similar values of 10.47, while the 50% replacement mix showed a lesser value of 10.26, indicating a slight increase in gas permeability. However, based on the error bars in Figure 4-7, the difference between the three replacement mixes remains negligible.

These results indicate that mixes with approximately 25% of recycled fine aggregates are similar to or can be compared to mixes without recycled fine aggregates in terms of gas permeation. However, 50% replacement values increase the gas permeation values by 2% compared to mixes without recycled fine aggregates. This decrease in OPI value at 50% RFA is attributed to the porous nature of RFA, which increased gas permeation within the concrete matrix. It should be noted that this increase does not exclude the quality of concrete from the excellent category.

For the 0.6 w/b ratio mixes, the 25% replacement mix showed a value of 10.31, indicating an increase in gas permeation of about 1.7% compared to the control mix, that showed a value of 10.49. These results indicated that concrete with RFA does influence the permeability of gas within the concrete microstructure. However, as can be observed in Figure 4-6, this influence is minimal, and the results can be well compared to the control mixes.

In contrast, the 50% RFA mix showed a value of 10.44, indicating only a slight increase of 0.5% compared to the control mix. Similar to the 0.45 w/b ratio mixes, it was noted that based on the error bars, all mixes had similar values, as seen in Figure 4-6.

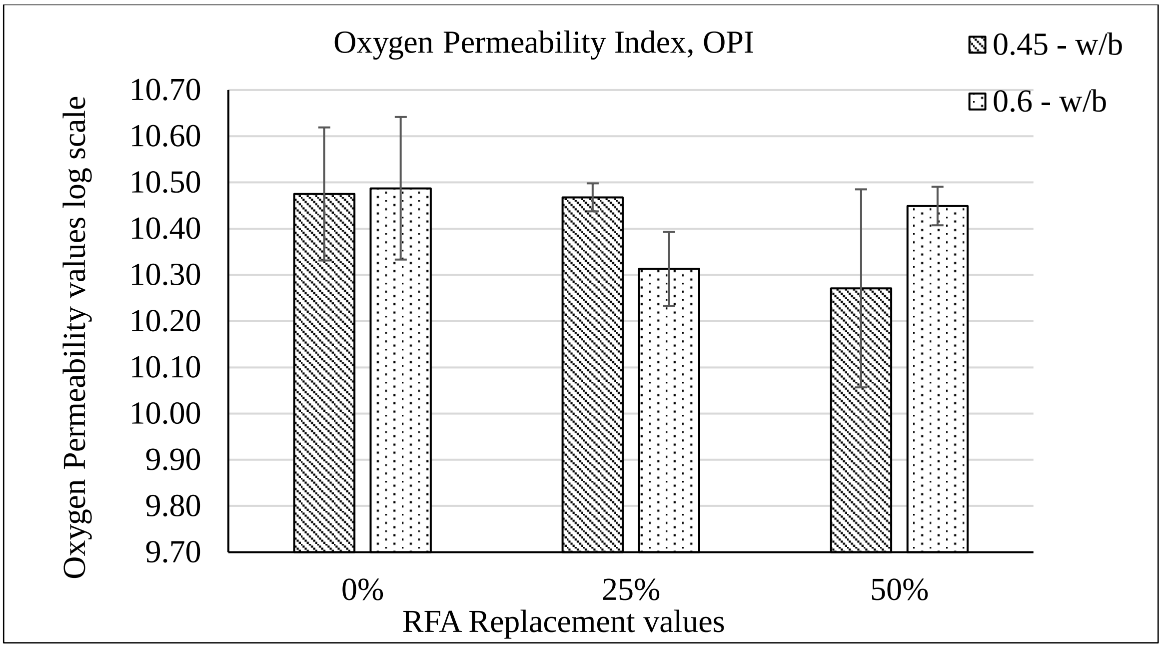


Figure 4-6: A summary of the oxygen permeability values for concrete of different replacement values of RFA.

For both w/b ratios, mixes with 50% replacement value of recycled fine aggregates were expected to have the highest value of gas permeation due to the higher amount of porous adhered mortar than the mixes with 0% and 25% replacement value of recycled fine aggregates. However, this expectation was only observed on the 0.45 w/b ratio mixes, as seen in Figure 4-6. This expectation was not observed for the 0.6 w/b ratio mixes, of which the OPI value at 50% replacement value of recycled fine aggregates mix indicates a lower gas permeation than 25% and a similar value to the 0% replacement of recycled fine aggregates. This opposite trend suggests further investigation of the concrete microstructure transport properties for mixes with a higher water binder ratio and a higher RFA replacement.

In a similar study with coarse recycled concrete aggregates, Olorunsogo & Padayachee (2002) observed that the Oxygen Permeability Index decreased as the RCA replacement ratio increased and even more as the curing age increased. This study concluded that increasing the recycled aggregates content from 0% to 100% resulted in a 15.0%, 16.0%, 10.0%, and 10.0 per cent drop in the value of OPI for concrete mixes cured for 3, 7, 28, and 56 days, respectively.

Similar to the results obtained in this study, Thomas et al. (2013) concluded that due to the limited porosity of the paste in lower w/b ratio mixes (w/b = 0.4), the movement of aggressive ions is delayed, resulting in a comparable behaviour for conventional and recycled concretes. The similarity in gas permeation between 0% replacement mix and 25% replacement mix instead of increase suggests an ongoing mechanism inside the concrete that blocks the pores and prevents the movement of gas in the concrete matrix. A slightly opposite trend is observed in the 0.6 w/b ratio mixes between the 25% replacement mix and 50% replacement mix. As the porosity of the concrete mix increases, the gas permeability decreases. This trend also suggests that even in higher w/b ratios, an ongoing mechanism exists in concrete mixes with RFA.

Hence at lower w/b ratios, the dense nature of concrete is the overriding factor, and therefore OPI results of 0% and 25% RFA content are similar. However, at 50% RFA content, the effect of RFA porosity increases the concrete porosity and subsequently gas permeation, and therefore the OPI value is reduced.

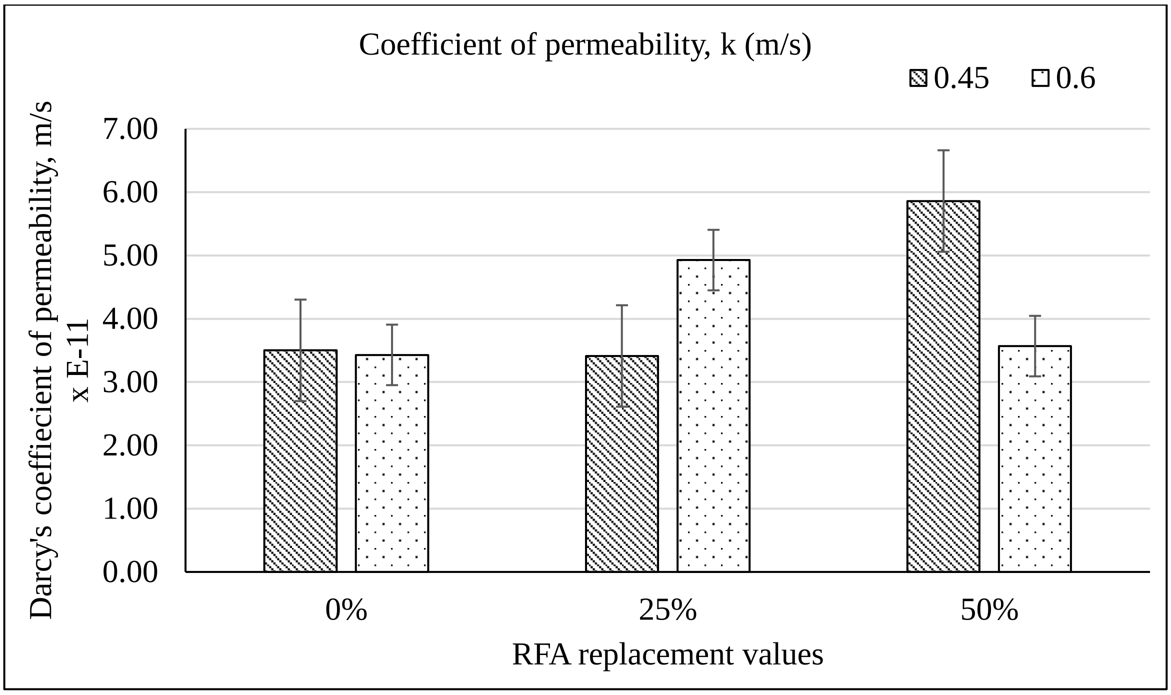


Figure 4-7: Darcy coefficient of permeability of concrete at different replacement values of RFA.

The coefficient of permeability results indicated that for the 0.45 w/b ratio mixes, a similar value is observed for the 0% and 25% mixes but a higher value for the 50% mixes. These results coincide with the oxygen permeability results since a lower permeability coefficient means lower gas penetration, and a higher permeability coefficient means higher gas penetration.

The same results are observed for mixes with 0.6 w/b ratio, showing that there is a higher coefficient of permeability for the 25% replacement mix than the 0% replacement mix. And the decrease in gas permeation is observed in the decrease of coefficient of permeability for the 50% replacement mix, which explains the decrease in gas permeation OPI values as seen in Figure 4-6.

4.5.1.2 Water Sorptivity Index test results

The water sorptivity index (WSI) represents the rate of capillary suction as normalised by the water-penetrable porosity of concrete. The water sorptivity results ranged between 7.8 to 9.5 mm/hr$^{0.5,}$ which, according to the criteria adopted for concrete durability tests, indicates a good quality of concrete, as seen in Figure 4-8. An outlier of poor quality of concrete is observed in the mix with a 50% replacement value of recycled fine aggregates for the 0.6 w/b ratios. Figure 4-8: A summary of water sorptivity values for concrete at different replacement values of RFA.

For the 0.45 w/b ratio mixes, the water sorptivity index results indicated a constant decrease in sorptivity of about 7% for each mix relative to the control mix as the replacement value of recycled fine aggregates increased from 0%, 25% and 50% replacement mixes, respectively. Since mixes with recycled concrete are reported to have more sorptivity than mixes with natural concrete, these results show an opposite trend in this case. These results suggest that lower w/b ratios lower the variability of the mixes, hence limiting the porosity of the new cement paste.

For the 0.6 w/b ratio, the results indicate a constant increase of the sorptivity value of about 18% and 10% as the replacement value of recycled fine aggregates increased from 0%, 25% and 50% replacement mix, respectively. In contrast to the 0.45 w/b ratio mixes, these results indicate that more sorptivity is observed in the mix, increasing the recycled fine aggregates per cent (Zega & Di Maio, 2011).

It was also observed that for both w/b ratios and replacement levels, all sorptivity values were very similar and in the same error bar range. Hence, there is a slight influence on water sorptivity properties for non-modified concrete with RFA.

Despite the fact that studies have shown that sorptivity and porosity are inversely related, laboratory studies have revealed that high or low sorptivity can be associated with high or low porosity and vice versa (Moore, Bakera & Alexander, 2021). And thus, concrete with a specific sorptivity value and lower porosity can have better durability properties than concrete with higher porosity values because higher porosity means more pore interconnectivity.

The porosity values indicated an increase in porosity as the replacement of recycled fine aggregates increased from 0%, 25% and 50%, respectively, for the 0.45 w/b ratio mix, as seen in Figure 4-9.

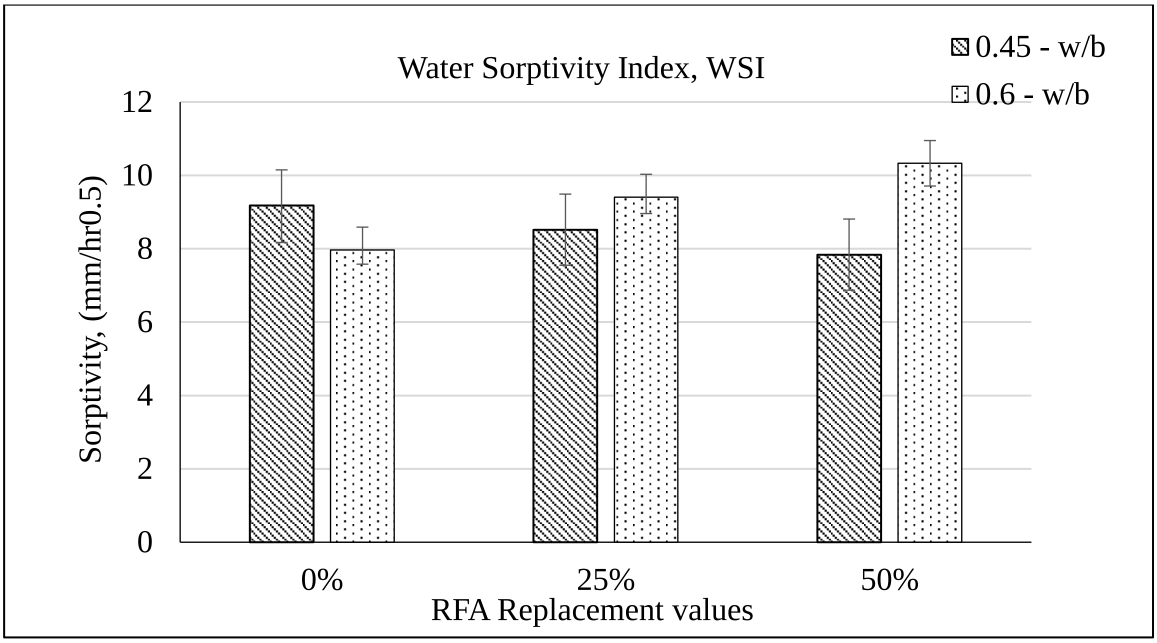


Figure 4-8: A summary of water sorptivity values for concrete at different replacement values of RFA.

This increase illustrates an opposite trend as compared to the water sorptivity results. As seen in Figure 4-8, the water sorptivity index for the 0.45 w/b ratio mixes decreases as the RFA replacement increases. These results indicate that, although the porosity of the concrete matrix increases, the sorptivity values can decrease depending on the constituents in the concrete matrix.

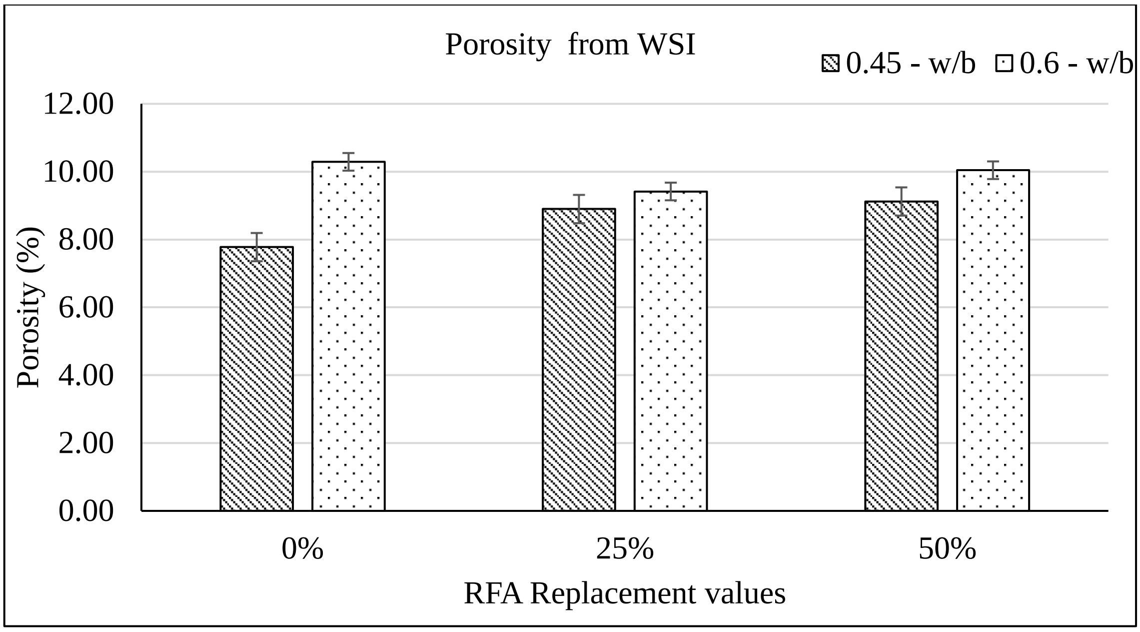


Figure 4-9: The percentage of water porosity for concrete mixes at different replacement values of RFA.

For the 0.6 w/b ratio mixes, a general decrease in the porosity values was observed as the replacement of recycled fine aggregates increased. For both the 25% and 50% replacement levels of RFA, a decrease of 0.1% and 0.02% was observed, respectively. The lowest porosity is observed in the 25% replacement mix compared to the 0% and 50% replacement mix. These values agree with the water sorptivity values observed in Figure 4-8.

Similar to the sorptivity values, despite the slight observations made, porosity values showed similar results within the same error bar range across the three replacement levels and two w/b ratios of the mixes.

Table 4-8: A summary of the coefficient of variation for the water sorptivity and porosity values.

	0.4 w/b ratio			**0.6 w/b ratio**		
	Control 1/ 0% RFA	**25% RFA**	**50% RFA**	**Control 2 / 0% RFA**	**25% RFA**	**50% RFA**
Coefficient of variation (Sorptivity)	10.99	11.36	12.36	4.87	4.79	6.01
Coefficient of variation (porosity)	8.60	5.50	5.09	3.06	1.96	1.69

4.5.1.3 Chloride Conductivity Index test results

The chloride conductivity index test measures the electrical conductance of concrete represented as the total charge in coulombs passed over a specified time. Conductance is connected to diffusivity, which is the material attribute that governs the rate of chloride ion penetration. The chloride conductivity index (CCI) results for this study ranged from 0.9 to 1.53 mS/cm. These results indicate that most of the mixes were of good quality, which means that the concrete mixes have good resistance to chloride penetration.

Generally, the average CCI values increased with an increase in w/b ratio, illustrating that a more porous concrete easily diffuses chloride ions. Low chloride conductivity values were observed in the 0.45 w/b ratio mixes compared to the 0.6 w/b ratio mixes, as seen in Figure 4-10. An increase in chloride conductivity index value depicts a decrease in the resistance of concrete to chloride penetration.

At 0.45 w/b ratio mixes, the results indicated a decrease of 13% of the CCI value at the 25% replacement mix and an increase of 13% of the CCI value at the 50% replacement mix compared to the control mix. These results indicate that adding recycled fine aggregates lowers the CCI value at the 25% replacement level but elevates the CCI value at the 50% replacement level compared to mixes without recycled fine aggregates. It was also observed that the error found within the 0.45 w/b ratio mixes was too high to compare to an average value and only two similar results were used for analysis.

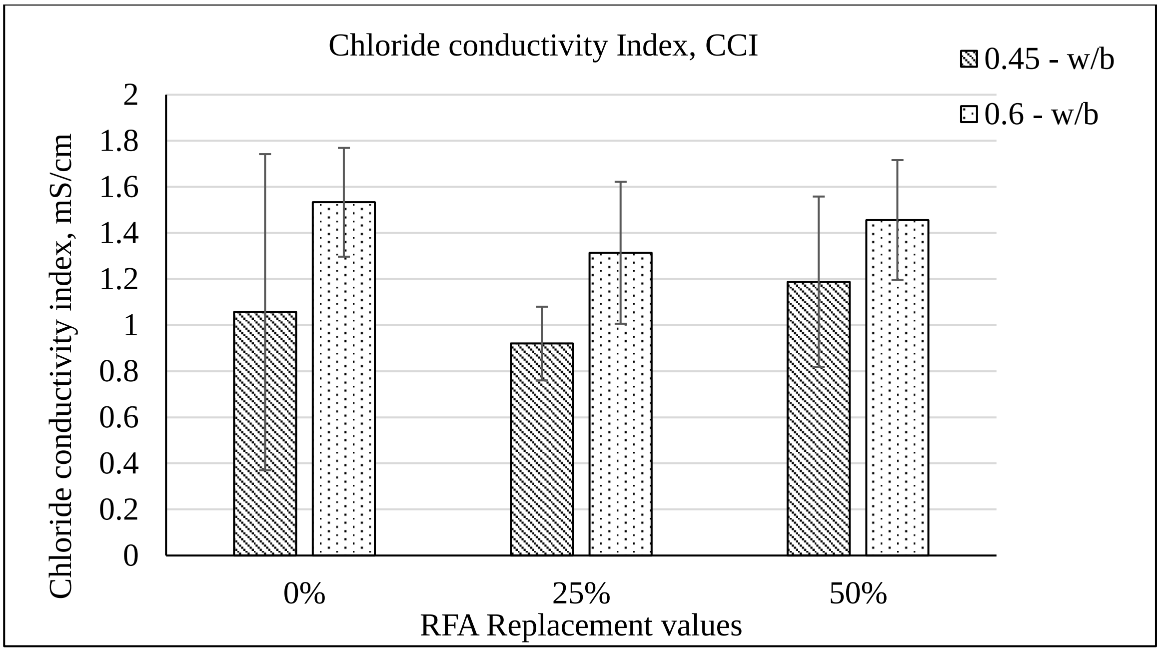


Figure 4-10: A summary of the chloride conductivity index values of concrete at different replacement values of RFA.

At the 0.6 w/b ratio, mixes without recycled fine aggregates indicated an overall higher CCI value than mixes with recycled fine aggregates. The results indicate a decrease of 14% and 5% of the CCI value for the 25% replacement mix and 50% replacement mix, respectively, compared to the 0% or control mix. These results also indicated a value of 1.53 mS/cm at the 0% or control mix for the 0.6 w/b ratio, which was concluded as the only mix with poor quality or low resistance to chloride penetration.

It was also observed that for all three replacement levels and two w/b ratio mixes, all CCI values were very similar and in the same error bar range. Hence, there is a slight influence on electrical conductivity properties for non-modified concrete with RFA.

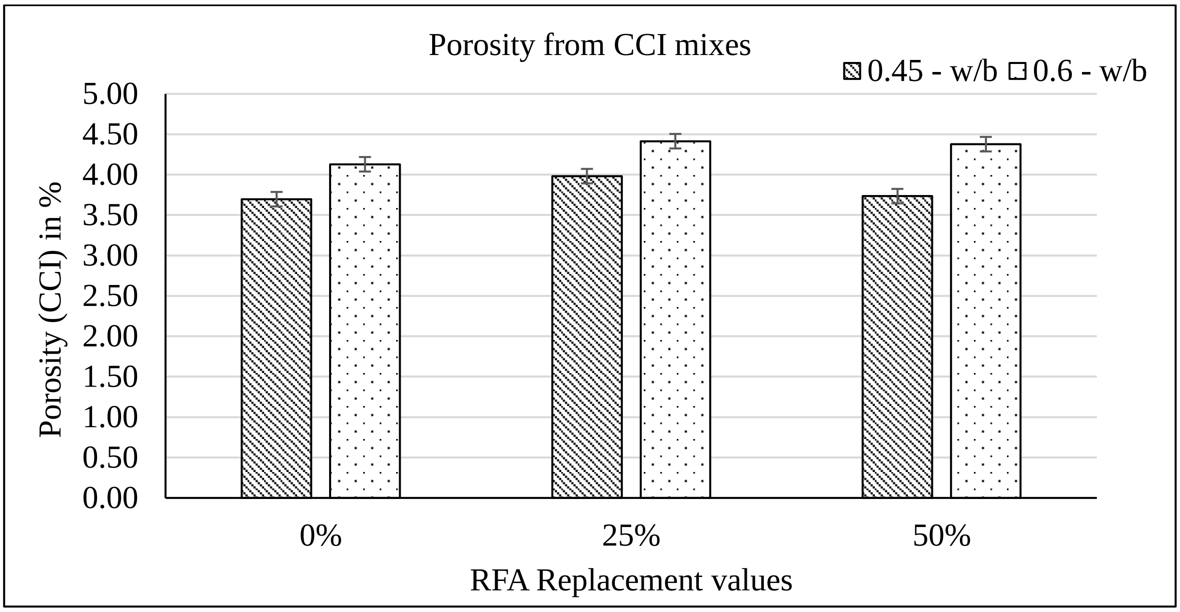


Figure 4-11: The percentage of porosity of NaCl for concrete mixes of different replacement values of RFA.

These results indicate that the addition of recycled fine aggregates has lowered the penetrability of chloride into the concrete matrix and thus improved the resistance of concrete to chloride penetration. These results suggest that the addition of RFA for both w/b ratios may have reduced the effective w/b ratio inside the concrete matrix, making the concrete denser, thus improving its durability.

The porosity percentage of the concrete mixes as calculated by the CCI test was observed to be between 3.5 - 4 % for the 0.45 w/b ratio and 4 - 4.5% for 0.6 w/b ratio mixes; as seen in

Figure 4-11, the porosity of the mixes increased with an increase in recycled fine aggregates content. Generally, the 25% replacement mix showed a higher average porosity value than the 0% and 50% replacement mix for both w/b ratios. Higher porosity values mean higher connectivity of the concrete matrix; however, it was observed that 25% of replacement mixes had lower CCI values. These results suggested that although the connectivity of the concrete matrix slightly increased, chloride conductivity was lowered.

For 0.45 w/b ratio mixes, an increase of 7.5% and 1% of the porosity value for the 25% and 50% replacement concrete mixes compared to the control mix was observed, respectively. A similar trend was observed for the 0.6 w/b ratio, as the 25% replacement level showed a higher porosity value of about 7% increase compared to the control mix and about 6% increase for the 50% concrete mixes.

Table 4-9: A summary of the coefficient of variation for the chloride conductivity and porosity values.

	0.4 w/b ratio			**0.6 w/b ratio**		
	Control 1/ 0% RFA	**25% RFA**	**50% RFA**	**Control 2 / 0% RFA**	**25% RFA**	**50% RFA**
Coefficient of variation (Conductivity)	64.94	17.36	31.11	15.38	23.45	17.83
Coefficient of variation (porosity)	3.917	4.824	3.7 84	6.210	3.097	5.680

4.5.2 Accelerated carbonation test results

The accelerated carbonation test measures the amount of carbonated material, taken as the depth of the carbonated front, which is the distance d (measured in mm) from the external surface of the concrete to the edge of the red-purple coloured region of the sample. This test measures the ingress of carbon dioxide gas due to exposure in the carbonation chamber, thus indicating the resistance of the cementitious mixes to carbon dioxide gas penetration.

Two concrete cubes were used per mix during the accelerated carbonation test, and six readings were taken per cube. Hence, twelve readings were recorded per concrete mix for each w/b ratio. The representative carbonation depth was taken as the average of two sides of the slices, as seen in Figure 4-12.

Readings were taken after 28 and 168 days of carbon dioxide exposure see Figure 4-13. Initially, testing was planned to be carried out after 28, 56 and 84 days of carbon dioxide exposure; however, due to lack of access to the laboratory caused by Covid-19 lockdown restrictions, these two later days could not be tested reported.

Results show that, due to the higher porosity of the 0.6 w/b ratio mix compared to the 0.45 w/b ratio mix, the 0.6 w/b ratio mixes showed more carbonation depth than the 0.45 w/b ratio mixes at all testing ages 28- and 168-days. This observation was attributed to the less dense microstructure that allowed gas penetration caused by the higher w/b ratio mixes. A similar observation was made by Zega & Di Maio (2011), concluding that the higher the w/b ratio, the poorer the permeability of the recycled aggregate concrete matrix, which increases the carbon dioxide absorption and, as a result, a higher carbonation depth.

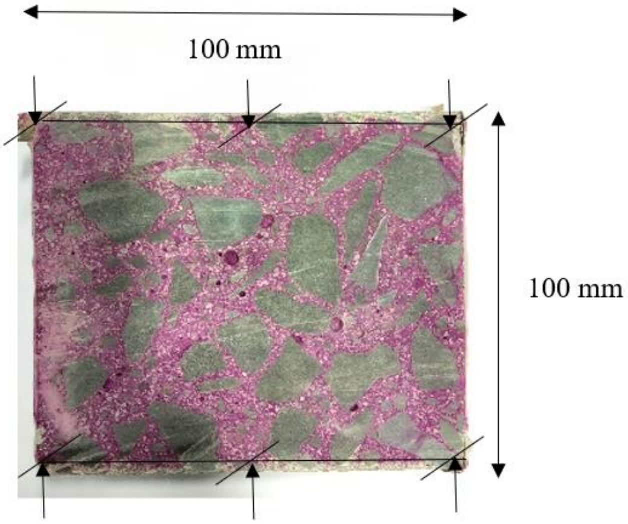


Figure 4-12 illustrates six different points considered for the average carbonation depth.

For the 0.45 w/b ratio, mixes with recycled fine aggregates showed no measurable carbonation at both testing ages compared to those without recycled fine aggregates (see Figure 4-13). As is subject to the hypothesis, the presence of adhered mortar on the surface of RFA provides an extra reserve of calcium hydroxide in the matrix and hence a higher “buffer capacity” against the carbonation process within the concrete matrix. These results indicated an improvement in resistance to carbonation penetration for the mixes with recycled fine aggregates.

In addition, the water absorption properties may have reduced the effective w/b ratio and hence made the concrete denser. A similar observation was made by Zega & Di Maio (2011), concluding that a lower w/b ratio positively influences porosity (by lowering it) and hence able to compensate for the use of a more porous aggregate such as RFA. It should be noted that for mixes without RFA, at 28 and 168 testing ages, a carbonation depth of 1.49 mm and 1.90 mm is measured, respectively. Hence the difference indicates an increase of 28% in carbonation for the control mixes between the two ages.

For the 0.6 w/b ratio, mixes with recycled fine aggregates showed a lesser degree of carbonation than mixes without RFA, as observed in Figure 4-13. These results indicate that even in higher w/b ratio mixes, the presence of extra cement might have improved the carbonation resistance and hence increased the durability properties of the concrete.

At 28 days of exposure, mixes with 25% and 50% replacement of RFA showed a decrease of 28.5% and 27.7% of carbonated depth compared to mixes with 0% replacement of RFA, respectively. At 128 days of exposure, mixes with 25% and 50% replacement of RFA showed a decrease of 41.2% and 15.3% of carbonated depth compared to mixes with 0% replacement of RFA, respectively. At both ages, it can be observed that the highest decrease occurred at the 25% replacement level of RFA, and hence being concluded as the optimum level of RFA replacement in terms of carbonation properties.

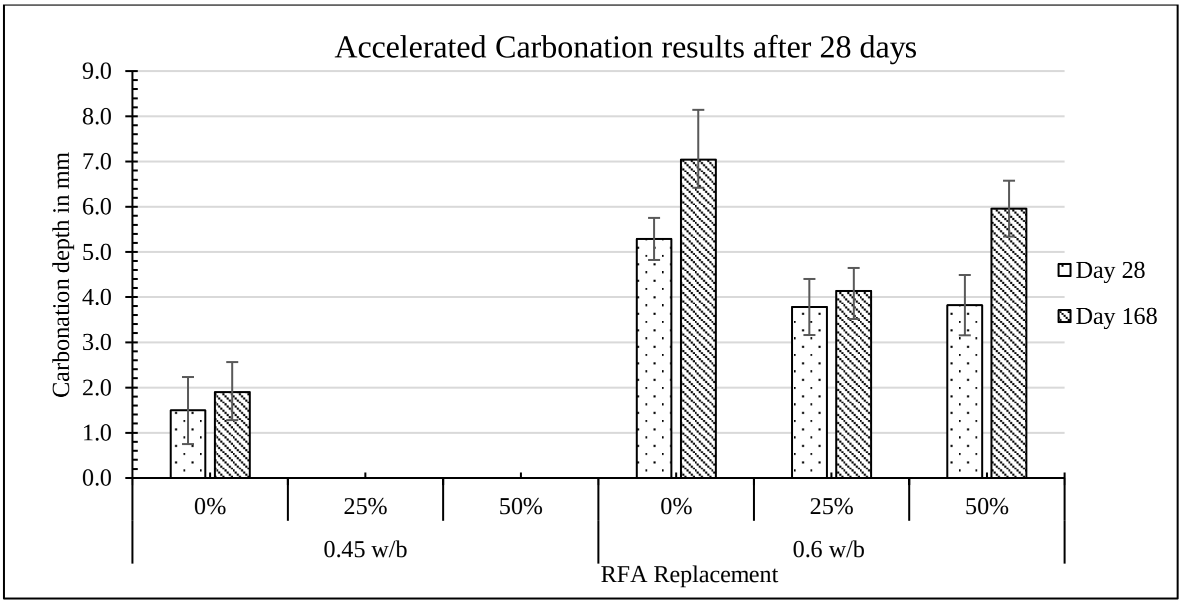


Figure 4-13: A summary of the accelerated carbonation test results

According to the hypothesis, the lower amount of measurable carbonation in mixes with RFA observed in Figure 4-13 may be attributed to RFA's extra Ca(OH)2 reserve, which may have reacted with CO_2 to produce $CaCO_3$. (Li, Xiao & Zhu, 2016; Kumar, Gurram & Minocha, 2017). The formation of more $CaCO_3$ from the carbonation process can cause a dense concrete microstructure and, hence, limit the progression of the carbonation front.

As discussed in the literature review, these results correspond to those of (Evangelista & de Brito, 2010; Silva et al., 2015; Kumar, Gurram & Minocha, 2017; Pedro, de Brito & Evangelista, 2017; Leemann & Loser, 2019; Kirthika & Singh, 2020). Although these results show that mixes with RFA have higher carbonation resistance to those without RFA, it should be noted that the use of high quality recycled concrete aggregates contributes to the reported properties. Hence, when a low-quality source of RFA is utilized, comparable results might be achieved to those of concrete without RFA.

Etxeberria et al. (2007), concluded that the carbonation rate of concrete with recycled coarse aggregates is comparable to that without recycled coarse aggregates under the condition that both the recycled aggregates and new mortar have similar gas permeability properties. In his conclusion, he reports that the additional alkalinity of recycled aggregate concrete due to adhered mortar will also contribute to a lower carbonation rate.

However, these results are in contrast with those of (Buyle-Bodin & Hadjieva-Zaharieva, 2002; Evangelista & de Brito, 2010; Evangelista & De Brito, 2014; Bravo et al., 2015; Fan et al., 2016; Nedeljkovi et al., 2021; Nedeljković et al., 2021) that reported on higher gas permeability in concrete made with recycled fine concrete than in concrete made with natural fine aggregates, illustrating a poor resistance to aggressive environments. They concluded that the high permeability of RCA also reduces the carbonation resistance of RCA-concrete or because it is already carbonated prior to being used in new concrete applications.

Despite the modification procedures such as extra water and cement content, the utilisation of recycled fine aggregates is limited to a recommended replacement level. This limitation is adopted due to their influence in lowering the durability properties of concrete. Hence, further research on the microstructure is to be conducted for the adoption of RFA.

4.5.3 Bulk diffusion test results

The bulk diffusion test measures the chloride content in a concrete sample. The chloride transport coefficient determined in this test uses an acid-soluble chloride profile derived from saturated specimens exposed to chloride solutions for a known period of time. This test measures the ingress of chloride ions due to exposure to external sources such as a sodium chloride solution and indicates the ease of chloride penetration into cementitious mixtures.

The percentage of chloride by mass of cement in the 0.45 w/b ratio mixes was slightly lower than the 0.6 w/b ratio mixes, as illustrated in Figure 4-14, Figure 4-15, Figure 4-16, Figure 4-17 and

Table 4-10. This observation was attributed to the dense microstructure of concrete in low w/b ratio mixes than in high w/b ratio mixes. This denser microstructure increases the resistance of chloride ions to penetrate the concrete matrix than in higher w/b ratio mixes with less dense microstructures.

The 0.45 w/b ratio illustrates that the depth of chloride ions in all the graphs has no significant variations after 120 days of exposure. Despite this general observation, 25% replacement of RFA shows a lower amount of chloride than both 0% and 50% replacement mixes. The surface chloride content for the control mix is 9.1 as a percentage of the mass of cement in the concrete, 7.24% for mix with 25% replacement of RFA and 10.05% for mix with 50% replacement level RFA, as seen in Figure 4-14. The results illustrate a decrease of 20.6% and an increase of 10.1% of the surface chloride content for mix with 25% and 50% replacement of RFA compared to the control mix, respectively. The presence of adhered paste could provide more calcium hydroxide to bind more chloride ions to further delay concrete contamination (Li, Xiao & Zhu, 2016; Kirthika & Singh, 2020). The results indicate that, for the 0.45 w/b ratio, concrete with a 25% replacement level of RFA has a decrease of about 9.52% as compared to the control mix and shows a similar depth of chloride penetration at a 50% replacement level with respect to their respective initial chloride content.

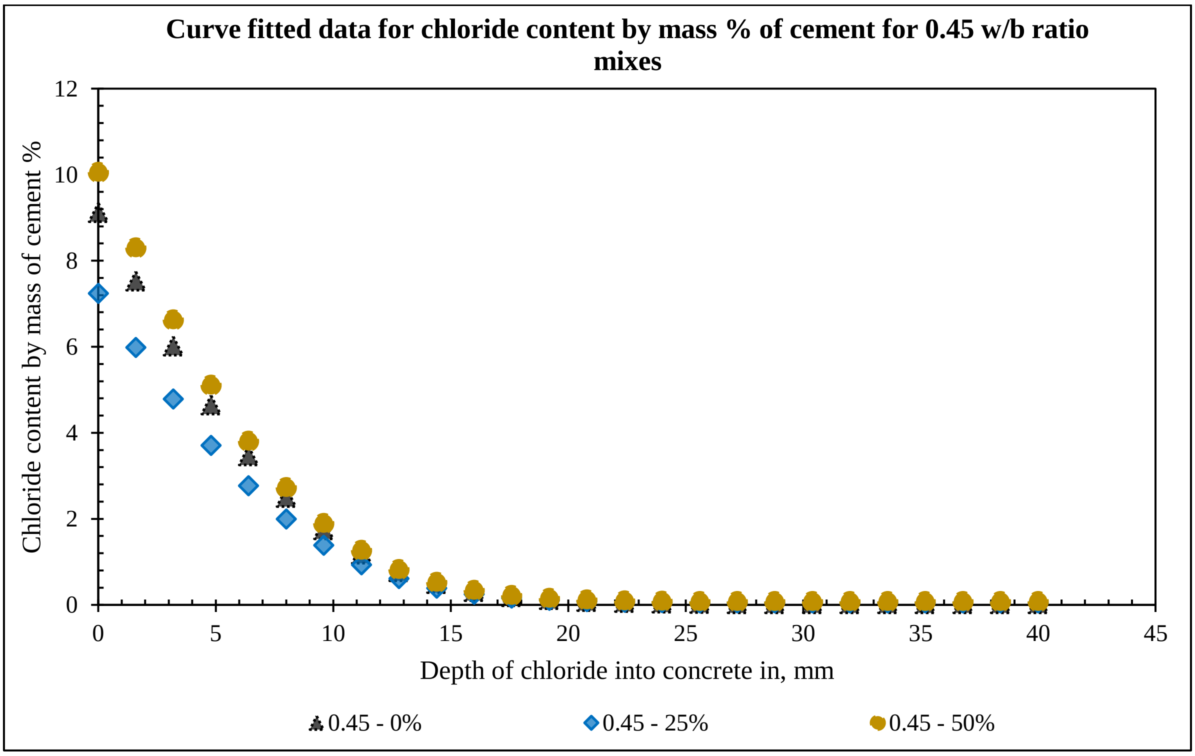


Figure 4-14: A summary of the calculated curve fitting for the 0.45 w/b ratio mixes at three different replacement levels of recycled aggregates

These results could be attributed to the lower porosity and a denser microstructure of the lower w/b ratio mix that has limited the ingress of chloride ions of the concrete when exposed to the NaCl environment (Thomas, Thaickavil & Wilson, 2018; Meddah, Al-Harthy & Ismail, 2020).

A constant or similar amount of chloride to the initial chloride content of the mix is attained at 33.6 mm, 30.4 mm, and 33.6 mm from the exposure surface for the 0%, 25% and 50% replacement levels of RFA, respectively, as seen in Figure 4-15 for the 0.45 w/b ratio mixes. A constant or similar amount of chloride to the initial chloride content of the mix is attained between 46 mm, 40mm and 48 mm from the exposure surface for the 0%, 25% and 50% replacement levels of RFA, respectively, as seen in Figure 4-17 for the 0.6 w/b ratio. These results indicate that the w/b significantly affects concrete's microstructure and overall porosity (Evangelista & de Brito, 2010; Kirthika & Singh, 2020).

As mentioned earlier, the increase in chloride permeability in the higher w/b ratio mixes is primarily due to the porous paste structure produced by the increased RFA concentration. A higher amount of chloride content is measured at the exposure surface of the 0.6 w/b ratio concrete mixes compared to the 0.45 w/b ratio concrete mixes. The surface chloride content for the control mix was about 9.4 as per cent of the mass of cement in the concrete, 11.55% for mix with 25% replacement of RFA and 10.52% for mix with 50% replacement level of RFA. This comparison can be seen in Figure 4-16. The results illustrate an increase of 22.6% and 11.7% of the surface chloride content for mixes with 25% and 50% replacement of RFA as compared to the control mix, respectively.

For the 0.6 w/b ratio, concrete with a 25% RFA replacement level for natural sand had a decrease of about 13% compared to the control mix and an increase of about 4.4% for the 50% replacement level of RFA with respect to their respective initial chloride content.

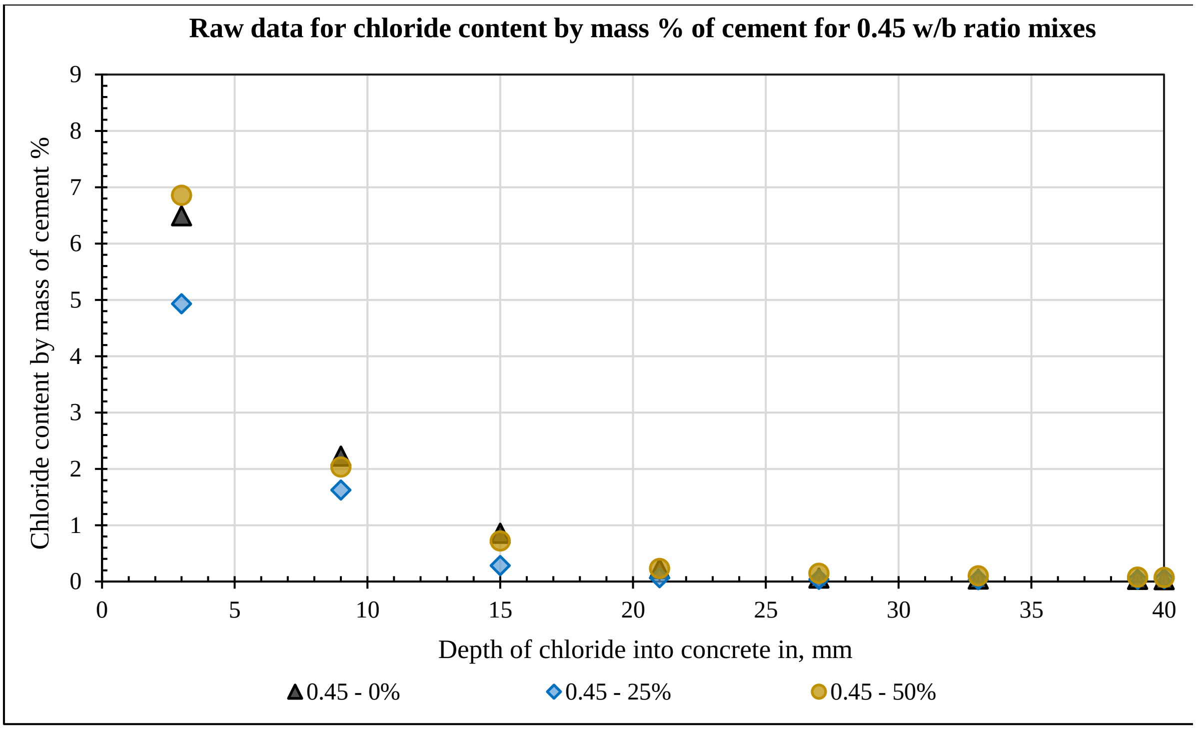


Figure 4-15:Curves for the raw data obtained from the 0.45 w/b ratio for 0%, 25% and 50% replacement levels of RFA

Furthermore, in the 0.6 w/b ratio mixes, the control mix indicates a slightly lower chloride content at the surface but later on retains a comparable amount of chloride ions within the concrete matrix. This indication was concluded to be due to the better surface finish of the concrete surface as compared to the mixes with RFA with a rougher surface finish, allowing easier penetration into the pores.

The opposite trend is observed in concrete with 25% and 50% replacement levels of RFA mixes, showing a slightly higher chloride content at the surface but, later on, lower chloride penetration within the concrete matrix. In summary, Figure 4-16 shows that mixes with RFA perform slightly better at resisting the penetration of aggressive ions within the concrete matrix than mixes without RFA. These observations were similar to those of (Li, Xiao & Zhu, 2016; Kirthika & Singh, 2020), indicating the presence of extra cement influences the durability properties of concrete made with RFA.

Similar observations were made by Zega & Di Maio (2011), who concluded that the durability of concrete made with recycled fine aggregates at 30% replacement level of fine aggregates was comparable to that without recycled fine aggregates. Furthermore, (Pedro, de Brito & Evangelista, 2017) concluded that the variations in chloride ion diffusion values were only slightly and hence the resistance of concrete made with RFA was similar to concrete made with natural fine aggregates. More scholars such as (Yehia et al., 2015) suggested that high packing density be considered in the use of recycled fine aggregates to achieve comparable durability properties of concrete made with RFA.

Various research work undertaken on chloride permeability on recycled aggregate concrete concludes that concrete with recycled aggregates has a lower resistance to chloride penetration than concrete with natural aggregates owing to the higher porosity found in recycled aggregates (Evangelista & de Brito, 2010; Bravo et al., 2015; Mardani-Aghabaglou, Tuyan & Ramyar, 2015; Pedro, de Brito & Evangelista, 2017; Thomas, Thaickavil & Wilson, 2018; Kirthika & Singh, 2020). It should be noted that most of these studies used modification techniques such as additional water and superplasticisers to boost the workability of RFA concrete, thereby compromising what influenced the lower durability properties of the concrete.

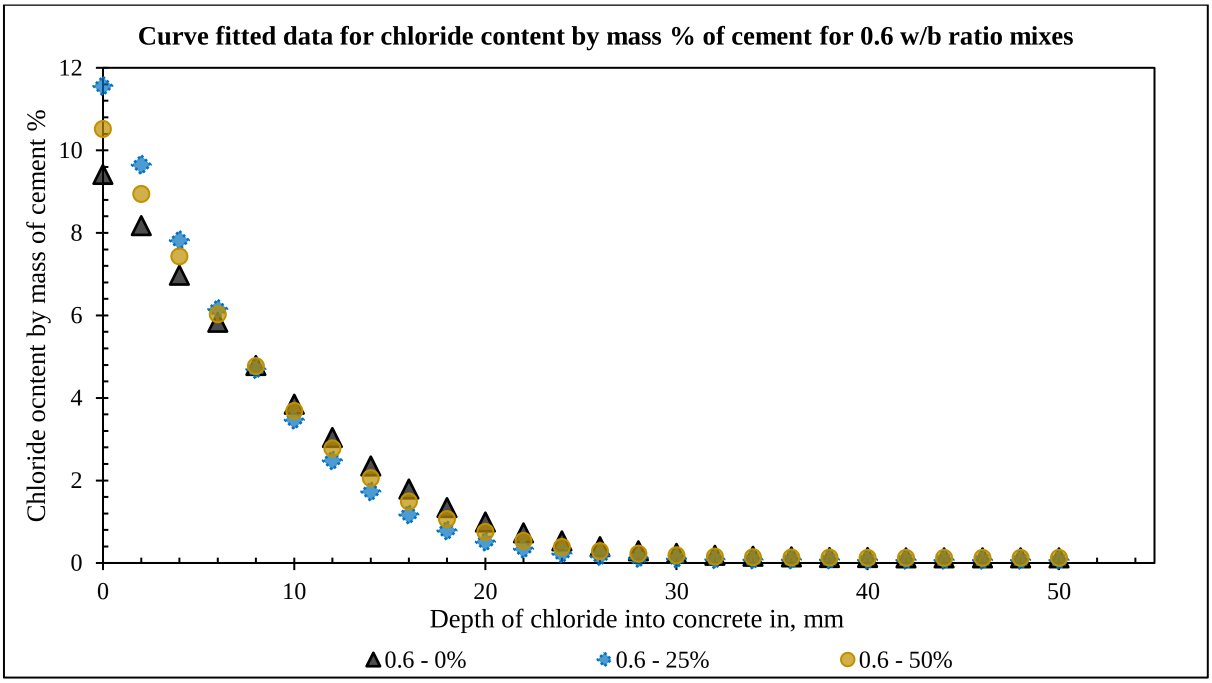


Figure 4-16: A summary of the calculated curve fitting for the 0.6 w/b ratio mixes at three different replacement levels of recycled aggregates

As seen in

Table 4-10, the 0.6 w/b ratio mix without RFA showed the highest chloride penetration, followed by the 50% replacement level of RFA. It should be noted that although slightly lower, mixes with a 25% replacement level showed the lowest chloride penetration into the concrete matrix. Thus, indicating that among the three replacement levels of RFA, mix with 25% replacement level of RFA performed optimally better than 0% and 50% replacement of RFA.

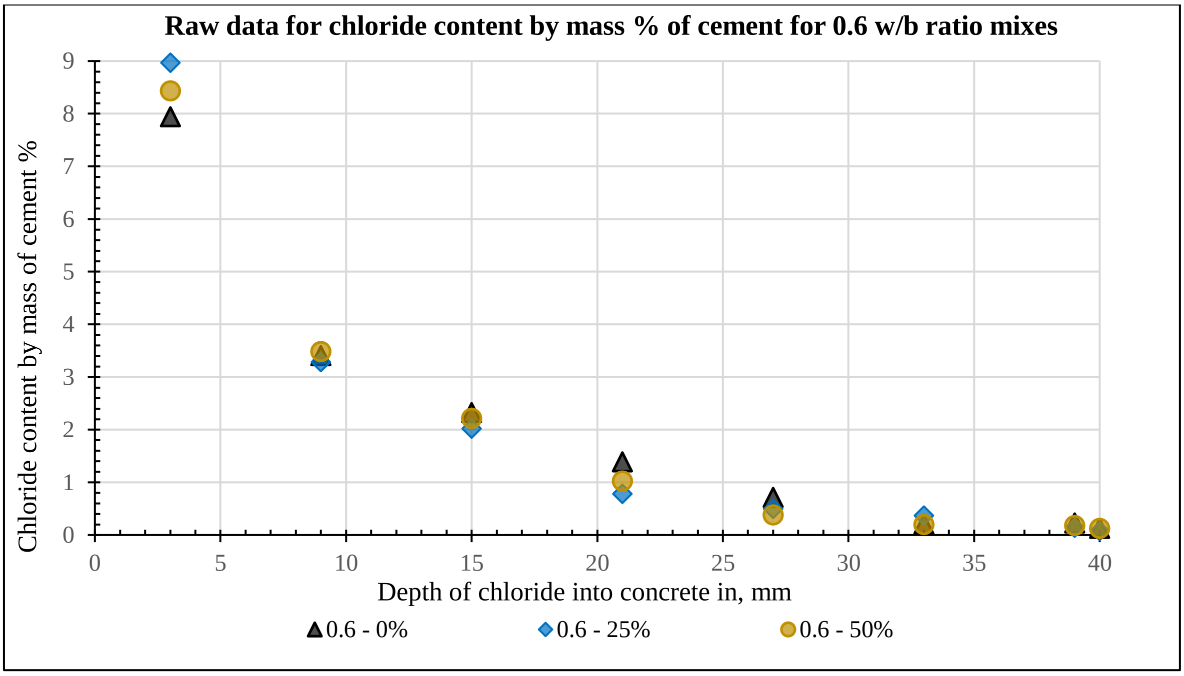


Figure 4-17: Curves for the raw data obtained from the 0.6 w/b ratio for 0%, 25% and 50% replacement levels of RFA

Table 4-10: A summary of the chloride penetration depth in the samples

	Chloride penetration depth with respect to the chloride threshold level, mm		
Percentage of RFA replacement	**0%**	**25%**	**50%**
0.45	16	14.4	16
0.6	26	22	24

The apparent chloride diffusion coefficient in m^2/s for the 0.45 w/b ratio is 3.2E-12 for the control mix 1, 2.6E-12 for mix with 25% replacement of RFA and 2.5E-12 for mix with 50% replacement level of RFA. The results illustrate a decrease of 19% and 21% of the chloride diffusion coefficient for the mix with 25% and 50% replacement of RFA compared to the control mix, respectively. These results coincide with the slight increase in chloride resistance observed in Table 4-10 for the lower w/b ratio mixes. A summary of the apparent chloride diffusion coefficient results is shown in Figure 4-18:.

The apparent chloride diffusion coefficient in m2/s for the 0.6 w/b ratios, is 6.9E-12 for the control mix 1, 4.4E-12 for mix with 25% replacement of RFA and 5.5E-12 for mix with 50% replacement level of RFA. The results illustrate a decrease of 36% and 20.3% of the chloride diffusion coefficient for the mix with 25% and 50% replacement of RFA compared to the control mix, respectively. These results coincide with the slight decrease in the chloride penetration observed in Table 4-10 for the higher w/b ratio mixes.

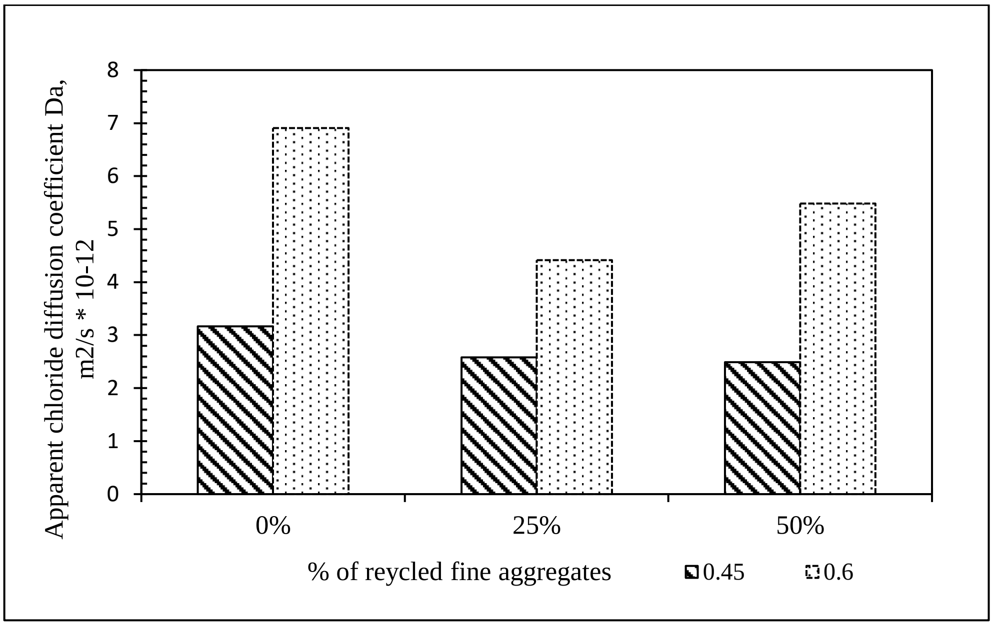


Figure 4-18: An illustration of the apparent chloride diffusion coefficients for the concrete mixes at different w/b ratios and replacement levels

4.6 Chapter summary and discussion

This chapter discusses the results and analysis of the experimental work conducted for concrete made with recycled fine aggregates. The particle size distribution and relative density tests are discussed under the characterisation of the fine aggregates. This section discusses the gradation, fineness modulus, and particle density of all three types of fine aggregates used in this research. In this section, it was observed that the increase of recycled fine aggregates across the different combinations had increased the amount of fine particles retained on the 0.075 mm sieve, and, similarly, the uniformity in the particle size distribution of the aggregates across the sieve sizes.

The fineness modulus of the replacement levels of aggregates ranged between 2.1 to 2.9, which means that the quality of sand was medium sand and not very fine or coarse sand. And lastly, the particle relative density of recycled fine aggregates showed the lowest value as expected due to the comparatively low density of the old mortar bound to the natural aggregate's grains.

Section three of this chapter summarises the fresh properties of concrete made with recycled fine aggregates. The slump test results and illustrations are summarised in this section. According to the results, the highest slump values were observed in the 0.6 w/b ratio mixes compared to the 0.45 w/b ratio mixes, owing to the higher amount of water found in the 0.6 w/b ratio mixes. At 0.45 w/b ratio mixes, the lowest slump value was recorded at the 25% replacement level of RFA, whilst at 0.6 w/b ratio mixes, the lowest slump value was recorded at the 50% replacement level of RFA. Generally, these values show that the addition of recycled fine aggregates does decrease the workability of concrete.

During the workability test, it was noted that although the properties of recycled fine aggregates significantly affect the fresh properties of concrete, the mechanical properties showed slightly better to no influence on concrete made with RFA.

Section four summarises the results and analysis of compressive strength results. The compressive strength results are reported regarding maturity and w/b ratio differences. The compressive strength results for both w/b ratios indicated that for mixes with RFA, slightly higher or comparable compressive strength values were observed compared to concrete without RFA at all testing ages for mixes. It was also observed that mixes without RFA increase gradually in compressive strength compared to mixes with RFA. Whilst the compressive strength gain for mixes with RFA shows stagnation during early ages and higher compressive strength values at older ages.

The durability properties of concrete made with fine recycled aggregates are summarised in section five via durability index tests results, accelerated carbonation tests and bulk diffusion test results. As summarised in the durability index section, all mixes showed an excellent quality of concrete during the Oxygen Permeability Index test despite having different replacement values of RFA. Furthermore, for the 0.45 w/b ratio, mixes with approximately 25% of recycled fine aggregates illustrated similar to or comparable values of gas permeation to mixes without recycled fine aggregates.

For the 0.6 w/b ratios, mixes with 50% replacement value of recycled fine aggregates illustrated a lower gas permeation than mixes with 25% replacement level and a similar value to mixes with 0% replacement level of RFA.

According to the criteria adopted for concrete durability index tests, all results for the WSI test indicated a good quality of concrete except for the mixes with a 50% replacement level of RFA at a 0.6 w/b ratio. For both 0.45 and 0.6 w/b ratio mixes, the water sorptivity index results indicated a constant decrease and increase of sorptivity value, respectively.

The chloride conductivity test indicated that most of the mixes were of good quality and hence had good resistance to chloride penetration. For the 0.45 w/b ratio mixes, the results indicated that the addition of recycled fine aggregates lowers the CCI value at 25% replacement level but elevates the CCI value at 50% replacement level compared to mixes without recycled fine aggregates. And for the 0.6 w/b ratio mixes, mixes without RFA indicated an overall higher CCI value than mixes with recycled fine aggregates.

During the accelerated carbonation test, mixes with recycled fine aggregates showed no measurable carbonation at both testing ages compared to those without recycled fine aggregates for the 0.45 w/b ratio. Of which according to the hypothesis, the lower amount of measurable carbonation in mixes with RFA was concluded to be attributed to RFA's extra Ca (OH)2 reserve, which may have reacted with CO2 to produce CaCO3. Similarly, for the 0.6 w/b ratio, mixes with recycled fine aggregates showed a lesser degree of carbonation than mixes without RFA.

The bulk diffusion test showed that the percentage of chloride by mass of cement in the 0.45 w/b ratio mixes was slightly lower than in the 0.6 w/b ratio mixes. Furthermore, the 0.45 w/b ratio mixes illustrate that chloride ions' depth in all the graphs has no significant variations after 120 days of exposure.

At the 0.6 w/b ratio mixes, the control mix indicates a slightly lower chloride content at the surface but later on retains a comparable amount of chloride ions within the concrete matrix. The opposite trend is observed in concrete with 25% and 50% replacement levels of RFA mixes, which show a slightly higher chloride content at the surface but later on lower chloride penetration within the concrete matrix. Section six summarises the summary of the chapter.

5 Conclusion and Recommendations

5.1 Summary of the study

The study investigated the influence on durability and other properties of concrete made with RFA through the effect of extra cement paste in the concrete matrix. The influence was hypothesized through an increase in time for aggressive substances to react with unhydrated cement found on the surface of RFA towards delaying the deterioration processes caused by chloride and carbonation attack.

Furthermore, the necessity to investigate concrete's mechanical and durability properties originates from the strength increase summarised in Section 4.4.1 and the delay in transportation of aggressive substances from outside the concrete summarised in Section 4.5.1. Therefore, considerations were made during the crushing process. A crushing method was adopted to retain the amount of adhered mortar on the surface of recycled fine aggregates. The adhered mortar plays a major role in the durability of RFA in concrete mixes.

The hypothesis of the study was investigated through the non-modification of RCA during the mix design process and by examining the influence of partial replacement of NFA with RFA on the durability and other properties of concrete. Since the surface of recycled fine aggregate contains an adhered mortar that is originally from the parent concrete, it is correlated that the existence of this layer influences the properties of this material. Due to the adhered mortar, cement hydration is likely influenced by the water absorbed during the mixing process. This research looked into the probability of a secondary reaction in concrete made with recycled concrete aggregate and its effect on durability properties. This influence was investigated through short-term and long-term durability tests such as the bulk diffusion and carbonation tests.

5.2 Broad conclusions

The presence of adhered mortar appears to foster a secondary reaction by providing excess cement paste and absorbed water that can increase the concrete's strength and prolong the time for aggressive ions to penetrate the concrete. This conclusion is inferred from the compressive strength results further discussed in Section 5.2.2. This observation was proposed to be validated through microscopic investigation tests such as SEM and XRD analysis as part of the recommendation.

General findings of this research, related to the challenges presented by RCA on the use of construction and demolition waste in the construction industry are reported as follows.

5.2.1 Challenges associated with the use of RCA

It was found that there are no challenges in utilising RCA for recycled aggregate concrete of average compressive strength of up to 35 MPa for new construction with no modifications or treatments made to the mixes. For both 0.45 and 0.6 w/b ratios, sufficient durability and other properties similar to those of natural aggregate concrete can be achieved. Further considerations made to the adaptation of the mixes are discussed in Table 5-1. The optimisation differing results from the two recycled concrete mixes have shown comparable to slightly higher properties than concrete with natural aggregates. Hence, the reuse of recycled concrete with an average strength of 35 MPa, is a practical alternative resource for construction purposes.

5.3 Properties of recycled concrete aggregates

The physical properties of recycled fine aggregates were assessed and reported as follows: (Objective 1)

- It was observed that the increase of recycled fine aggregates across the different combinations had increased the amount of fine particles retained on the 0.075 mm sieve and, similarly, the uniformity in the particle size distribution of the aggregates across the sieve sizes. The gradation of RFA showed a more uniformly distributed curve than dune and crusher sand, individually. However, combinations of RFA at 25% and 50% complied with the standard gradation for aggregates as stipulated in SANS 197, SANS 201 and ASTM C33.
- The relative density of RFA was found to be higher than that of NFA. The decrease in density was attributed to the old mortar bound to the aggregate’s grains. However, the wet densities of the mixes were very similar.
- As further elaborated in the water sorptivity conclusion, mixes with recycled concrete aggregates were found to have a higher water absorption capacity than mixes with natural fine aggregates. As McNeil & Kang (2013) concluded, the water absorption capacity of recycled aggregates is directly influenced by the amount of residual adhered mortar. And RCA’s higher water absorption and porosity are due to the adhered residual

mortar on the underlying rock, allowing the recycled aggregates to hold more water in their pores than natural aggregates.

Technically, recycled concrete aggregates find limited application because of their reported inferior properties compared to concrete with natural aggregates. This research has shown net positive and similar results compared to concrete with natural aggregates. These net positives are attributed to the presence of adhered cement paste and the higher porosity of the recycled fine aggregates combined with non-modifications in the concrete mixes.

Table 5-1:Gaps associated with the use of recycled fine aggregates in the construction industry

Challenge and effects	**Consideration made and gaps filled**
Variability. Variability originates from the material source, environmental exposure and strength class of the material.	RFA was sourced from concrete panels in the N2 road expansion project with an average compressive strength of 35 MPa. The environment is subject to the aggressivity of weather and ions, which is categorised as an uncontrolled environment.
Quality Control. Quality control of recycled aggregates is done during the demolition and sorting stage.	This research work conducted quality control using one site source and validated through material characterisation and strength tests.
Standards and specifications. The lack of well-developed guidelines for the quality control of recycled aggregates prevents its more comprehensive utilisation in new concrete.	No new standard or specification was used for this study. All tests were conducted according to the current standards and specifications for using natural materials in concrete production and testing.
Research vs actual construction. Research work in the laboratory on the quality control of recycled aggregates is more demanding and thorough than in practical uses.	Although this research work was thoroughly conducted in the laboratory, the material was sourced from an actual construction site.

5.3.1 Recommended level of RFA replacement

(Objective 2 and 3)

The recommended level of RFA according to the analysis chapter as seen through the particle size distribution, workability tests and transport properties was concluded as follows.

The replacement of RFA at both levels complied with the grading limits specified in ASTM 33, as seen in Figure 4-2. During workability, the lowest slump value was recorded at the 25% replacement value for the recycled fine aggregates mix, as seen in Figure 4-3. At 25% replacement levels of RFA, slightly higher compressive strength values were observed than at 50% replacement level of RFA as well as the highest increase was observed at the 25% than 50% replacement levels of recycled fine aggregates even after 112 days. It was also observed that for both w/b ratios and replacement levels, all permeability, sorptivity and conductivity values were very similar and in the same error bar range. Thus, indicating that among the three replacement levels of RFA, mix with 25% replacement level of RFA performed optimally better than 0% and 50% replacement of RFA.

5.3.2 Properties of concrete made with recycled concrete aggregates

Fresh concrete made with RFA was stiffer and resulted in a lower slump than concrete made with natural aggregates. This increased stiffness was attributed to the presence of adhered mortar found on the surface of the recycled concrete aggregates, and the associated absorption of mixing water. The fresh properties of concrete were variable in terms of slump standards. Despite the 0.45 w/b ratio mix appearing very stiff in the mixer and the workability test, the concrete was easy to compact and showed good mix consistency. Thus, it appeared that despite the stiff nature of the concrete, with proper compaction methods, the mix can be vibrated easily for the destined structure.

For the 0.6 w/b ratio, the concrete appeared to be workable and provided a good mix consistency. Matias et al. (2013) reinforced these results by reporting that maintaining the aggregates gradation and fresh concrete properties design may lead to compressive strength values similar to conventional concrete.

5.3.2.1 Compressive strength results

The compressive strength results for the parent concrete gave an average strength of 35.7 MPa. Compressive strength results of the mixes indicated that, at 0,45 w/b ratio, slightly higher comparable compressive strength values were observed than mixes with 0.6 w/b ratios and the highest strength values were observed at 25% replacement of RFA for both w/b ratios. Generally, the compressive strength results indicated that recycled fine aggregates positively affected the concrete’s strength. The addition of recycled fine aggregates showed a low increase in compressive strength during early ages, specifically at 28 days; however, this increase is inversed later, as seen at 112 days. It is observed that RFA mixes with a higher w/b ratio only attain higher compressive strength at a later age than RFA mixes with a low w/b ratio. This delay in the increase of strength in a higher w/b ratio mixes was consistently observed for all replacement levels. A further investigation of the cause of delay in the increase of compressive strength in higher w/b ratio mixes with RFA is recommended in future work.

The compressive strength of the concrete mixes slightly differed at the early ages of 3 and 7 days; however, at 28 days, the mixes with RFA and those without had very similar compressive strengths. These results indicated that when utilizing RFA, the intended strength might be delayed during early ages, nonetheless attained during later ages, i.e., above 28 days. It was also observed that mixes without RFA increase gradually in compressive strength compared to mixes with RFA. Whilst the compressive strength gain for mixes with RFA shows stagnation during early ages and higher compressive strength values at older ages.

5.4 Durability properties of concrete

(Objective 4)

According to the criteria adopted for concrete durability tests, during the OPI results, all mixes showed a value of more than 10 of the negative log of the Darcy coefficient of permeability (k) which indicated an excellent concrete despite having different replacement values and w/b ratios. The similarity in gas permeation between 0% and 25% replacement of RFA in the lower w/b ratio mixes suggests an ongoing mechanism inside the concrete that densifies the microstructure and prevents the movement of gas in the concrete matrix. At 50% replacement level, a slight increase of gas permeation was observed, attributed to the porous nature of RFA, which apparently increased gas permeation within the concrete matrix.

At higher w/b ratio mixes, a slight increase of gas permeability is observed at both 25% and 50% replacement levels of RFA compared to the 0% replacement of RFA, indicating that the increase of RFA does influence the gas permeability of concrete. However, it was also concluded that the increase was minimal for both w/b ratios and the results were very similar compared to control mixes.

The WSI results indicated a good quality of concrete according to the criteria adopted for concrete durability tests. An outlier of poor quality of concrete is observed in the mix with a 50% replacement value of recycled fine aggregates. For the 0.45 w/b ratio, the water sorptivity index decreases as the RFA replacement increases, indicating a denser microstructure and hence improvement in the quality of concrete. For the 0.6 w/b ratio mixes, a general increase in the sorptivity values was observed as the replacement of recycled fine aggregates increased. However, the porosity values decrease as recycled fine aggregates' replacement increases. The lowest porosity was observed in the 25% replacement mix compared to the 0% and 50% replacement mix.

The CCI results reported all good quality concrete except at the 50% replacement level of RFA for the 0.6 w/b ratio. This indication of a good quality of the concrete mixes suggested that the mixes were of high resistance to chloride penetrability.

For the 0.45 w/b ratio mixes, the addition of recycled fine aggregates lowers the CCI value at 25% replacement level but increases the CCI value at 50% replacement level compared to mixes without recycled fine aggregates. Although, a higher porosity value was reported at the 25% replacement mix than the 0% mix and 50% replacement mix for both water binder ratios.

For the 0.6 w/b ratio mixes, the results indicate that the addition of recycled fine aggregates has lowered the penetrability of chloride into the concrete matrix and thus improved the resistance of concrete to chloride penetration. For the 0.6 w/b ratio, the 0% replacement level of RFA mix indicated an overall higher CCI value than other mixes, concluding that there is a lower chloride conductivity in mixes with RFA compared to mixes without RFA.

In summary, according to OPI, WSI and CCI results, the 25% replacement level of RFA is the recommended replacement level for standard durability properties to be achieved.

5.4.1 Carbonation results

Carbonation results indicated an increase in carbon dioxide penetrability with an increasing w/b ratio of the mixes. Hence, lower w/b ratio mixes showed lesser carbonation than higher w/b ratio mixes.

For the 0.45 w/b ratio, mixes with RFA showed no measurable carbonation at 28 or 168 days. During these testing ages, mixes without RFA had carbonated to a quantifiable amount of 1.7 mm from the surface of the concrete samples. For the 0.6 w/b ratio, mixes with RFA showed less carbonation than mixes without RFA.

As is subject to the hypothesis in Section 1.4, the presence of extra cementitious material available for further hydration may have improved the durability properties of the concrete by reducing the carbonated material through delaying the carbonation process. In addition, the water absorption properties may have reduced the effective w/b ratio and hence made the concrete denser. Overall, mixes that had partial replacement of RFA were less carbonated than mixes without RFA, implying that an improvement in resistance to carbonation penetration was observed for mixes with RFA compared to mixes without RFA.

5.4.2 Bulk diffusion results

Generally, the percentage of chloride content in the 0.45 w/b ratio mixes was slightly lower than in mixes with a 0.6 w/b ratio. For the 0.6 w/b ratio, a higher amount of chloride is measured at the exposure surface compared to the 0.45 w/b ratio.

For the 0.45 w/b ratio, the results illustrate a decrease of 21% of the surface chloride content for mixes with 25% replacement of RFA compared to mixes without RFA and an increase of 10% for mixes with 50% replacement of RFA. The apparent chloride diffusion coefficient illustrates a decrease of 19% of the chloride diffusion coefficient results for the mix with 25% replacement of RFA compared to the control mix and a decrease of about 21% for the mix with 50% replacement RFA.

These results indicate that at a 25% replacement level of RFA, lower chloride content is observed than at a 50% replacement level of RFA. Owing to the hypothesis, the presence of adhered paste could be providing more calcium hydroxide to bind more chloride ions to delay the contamination of concrete further, as reported by (Li, Xiao & Zhu, 2016; Kirthika & Singh, 2020). The opposite is seen for the 50% replacement level, which discards it as the recommended replacement level for RFA in concrete mixes.

For the 0.6 replacement level of RFA, the results illustrate concrete with a 25% replacement level of RFA had a decrease in chloride content of about 13% compared to the control mix and showed an increase in chloride content of about 4% for the 50% replacement level RFA. Mixes without RFA indicated a lower chloride content penetration at the surface compared to mixes with RFA but retained more chloride ions within the concrete matrix as the concrete aged compared to mixes with RFA.

The opposite trend is observed in concrete with 25% and 50% replacement levels of RFA mixes, which showed lower chloride penetration within the concrete matrix. These results concluded that mixes with RFA showed higher resistance to the penetration of aggressive ions within the concrete matrix than mixes without RFA.

The apparent chloride diffusion coefficient illustrates a decrease of 36% of the chloride diffusion coefficient for the mix with 25% replacement of RFA compared to the control mix and a decrease of about 20% for the mix with 50% replacement RFA.

5.5 Conclusion

It should be noted that most research work on the use of RFA includes the addition of superplasticisers, mineral additives and extra water during mixing. None of these techniques were included during this research work to form a basis of comparison and assist in understanding the use of RFA individually. Hence the success of this research work would enable the use of RFA in construction sites without further economic obligations.

When originating from a known source, i.e., an average strength of 35 MPa, the results also show that a replacement ratio of 25% of RFA does not significantly affect the performance of recycled aggregate concrete mixes. Furthermore, recycled aggregate concrete performs satisfactorily according to known mechanical standards and has comparable durability to natural aggregate concrete. It should be noted that these results were made from the considerations outlined in Table 5-1 with regards to the use of recycled aggregates in concrete production.

5.6 Recommendations for further work

- Careful attention must be paid to achieve adequate compaction of the mixes during site mixing and casting with recycled fine aggregates. Concrete strengths may vary due to different compactive efforts applied, which must be factored into site quality control procedures.
- On the fresh properties of concrete made with recycled fine aggregates, a w/b ratio between 0.45 and 0.6 indicated a potential good limit for adopting recycled concrete use application with no modifications.
- Although this research work illustrates a good practical comparison between concrete with and without RFA for both replacement levels of 25% and 50%, further analysis on a microscopic investigation of the concrete microstructure should be conducted to analyse the cause of an increase in compressive strength and higher durability properties in concrete with RFA. A clear understanding of the transportation pathways in concrete made with recycled concrete aggregates can only be done through microscopic investigation and chemical properties testing. Hence more microscopic

investigation should be done on the hydration process in concrete made with recycled fine aggregates without modification.

- During the compressive strength test, it was observed that RFA mixes with a higher w/b ratio only attain higher compressive strength at a later age than RFA mixes with a low w/b ratio. This delay in the increase of strength in a higher w/b ratio mixes was consistently observed for all replacement levels. A further investigation of the cause of delay in the increase of compressive strength in higher w/b ratio mixes with RFA is recommended in future work.
- Various work has been done on recycled aggregates for the coarse fraction and fewer on the fine fraction with reasonable modifications. It should be noted that although this work illustrates a good start on the use of RFA without any modifications, further investigation on the relationship between particle size distribution and durability of concrete made with recycled fine aggregates should be addressed. In addition, due to the presence of hardened cement paste (mortar) on recycled concrete aggregates, there is a high significance to conduct material characterisation on RCA compared to natural aggregates. Characteristics such as porosity and grading requirements and significant source fluctuations in quality control remain some of the biggest challenges in providing heterogeneity control of RCA.
- The source of recycled aggregate concrete is crucial in RFA use in concrete applications. The findings of this research are subject to the origin of the RFA. With a compressive strength of 35 MPa, recycled aggregates concrete can be used as an alternative material for natural fine aggregates at a 25% replacement level.

Whilst this research has attempted to focus on a single hypothesis and test the general understanding of the use of RFA without modification, a more robust, sound and comprehensive analysis and interpretation of all data pertaining to recycled aggregates and concrete made with recycled fine aggregates is still required to ensure that full confidence can be gained in adopting the knowledge that exists. Furthermore, legislative requirements such as concrete recycling policies and strategies that strive to coordinate diverse stakeholders (e.g., client, contractor) in managing construction and demolition debris are absent.

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7 Appendix

A. Summary of the calculations done for the 0.45 w/b

Water $= (\frac{185}{1000} \times 100)$ = 18.5%

Cement $= (\frac{411}{3140} \times 100)$= 13.09%

Coarse Aggregates $= (\frac{986}{2720} \times 100)$= 36.25%

Sand or Fine Aggregates = (100% - (18.5%+13.09%+36.25%)) = 32.16%

Only 32.16% is to be replaced with recycled fine aggregates.

Hence, both crusher and dune sand will have 16.08% in the total mix design volume in the control mix.

0% Replacement of recycled fine aggregates A

Crusher sand required in the control mix.

$$= (\frac{16.08}{100} \times (\text{Crusher sand particle relative density})) \tag{1}$$

$= (\frac{16.08}{100} \times 2720)$ =

Dune sand required in the control mix

$$= \left(\frac{16.08}{100} \times (\text{Dune sand particle relative density})\right) \tag{2}$$

$= (\frac{16.08}{100} \times 2650)$ =

25 % Replacement of Crusher Sand

The 25% replacement of recycled fine aggregates, the crusher, dune, and the recycled fine percentage is 8.04%, 16.08% and 8.04%, respectively.

Crusher sand required in the control mix

$$= (\frac{8.04}{100} \times (\text{Crusher sand particle relative density})) \tag{3}$$

$$= (\frac{8.04}{100} \times 2720) =$$

Dune sand required in the control mix

$$= (\frac{16.08}{100} \times (\text{Dune sand particle relative density})) \qquad (4)$$

$$= (\frac{16.08}{100} \times 2650) =$$

RFA required in the control mix

$$= (\frac{16.08}{100} \times (\text{RFA particle relative density})) \qquad (5)$$

$$= (\frac{8.04}{100} \times 2580) =$$

50% Replacement of Crusher sand

Dune sand required in the control mix

$$= (\frac{16.08}{100} \times (Dune\ sand\ particle\ relative\ density)) \qquad (6)$$

$$= (\frac{16.08}{100} \times 2650) =$$

RFA required in the control mix

$$= (\frac{16.08}{100} \times (RFA\ particle\ relative\ density)) \qquad (7)$$

$$= (\frac{16.08}{100} \times 2580) =$$

B. Summary of the calculations done for the 0.6 w/b

The same procedure was conducted for the 0.6 water binder ratio design to achieve the mix design's required amount of fine aggregates.