Evaluation of Mechanical and Durability Properties of Concrete with Recycled Materials for its use in Interlocking Concrete Pavement

by

Shreenita Chhetri

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Applied Science

in

Civil Engineering

Waterloo, Ontario, Canada, 2022

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The use of coarse recycled concrete aggregates (CRCA) in concrete as a replacement for natural aggregate (NA) has recently sparked a lot of attention. The use of CRCA is gaining acceptance as more research into its performance is conducted. Similarly, incorporating supplementary cementitious materials (SCMs) into concrete mixes helps to reduce cement consumption and carbon dioxide emissions. The substitution of NA for CRCA and conventional cement for SCMs is a potential step toward more sustainable concrete that conserves natural resources while reducing the environmental impact of concrete. As a result, using these materials is a more eco-friendly option.

This study focuses on the mechanical and durability properties of concrete mixes, including CRCA and SCMs, for use in interlocking concrete pavers (ICP). Three concrete mixes with varied ratios of CRCA and SCMs are compared to the performance of the control mix. Ground Glass Puzzolans (GP) and Ground Granulated Blast Furnace Slag were employed as SCMs in this investigation. The fresh properties of the mixes, including slump and air content, were investigated. Compressive strength, shear strength, splitting tensile strength, water absorption, and freeze-thaw resistance are among the hardened characteristics of diverse mixes investigated.

The results show that concrete mixtures containing CRCA and SCMs performed similarly to the NA and general use limestone cement (GUL) control mix (CM) in terms of compressive strength and even outperformed the CM in terms of water absorption and freeze-thaw durability. A general trend of decreasing compressive strength with increasing percentage replacement of CRCA was observed; however, compressive strength was seen to improve with the addition of SCMs. The increase in the quantity of CRCA in concrete mixtures led to a decrease in the values of shear strength and splitting tensile strength and the addition of SCMs did not significantly contribute to these values. The water absorption value is observed to increase in the mixture containing only partially replaced CRCA, but it is observed to be better in the mixture containing CRCA and SCM. Compared to the CM and mix with only CRCA, the freeze-thaw durability measured in terms of mass loss was better for mixes with CRCA and SCMs. The findings of this study provide strong evidence to encourage the use of CRCA and SCMs to partially replace NA and conventional cement and serve as a step toward more sustainable concrete.

Acknowledgments

I would like to express my deepest gratitude to my supervisor Dr. Susan Tighe, for the constant support, patience, motivation, and guidance throughout my research journey. I could not have imagined having a better supervisor and mentor for my research and for life. I would like to thank my co-supervisor, Dr. Pezhouhan Tavassoti for all his support. I would also like to thank the University of Waterloo and the Department of Civil Engineering, for letting me fulfill my dream of being a student again and showering me with endless opportunities.

I am also extremely grateful to Dr. Hanaa Al-Bayati for her guidance, assistance, and suggestions throughout the project. I would also like to thank Dr. Seyedata Nahidi for all the help offered in the lab. I am thankful to my friend and my lab partner, Xinyue Ni (Crystal) for being there for me throughout. I would also like to acknowledge the support of all my colleagues at CPATT, you guys are awesome. I am also thankful to the entire team at PSI technologies, Dr. Vimy Henderson, Dr. Daniel Pickel and especially Mathias Cawthra for his help in the lab. I would also like to thank Richard Morrison and Peter Volcic for all the help that they rendered in conducting the lab tests.

I am deeply grateful to my parents, my brother, and my entire family for their continuous support, for helping me survive all the stress, and for never letting me give up. To my husband, Niwit Aryal for his encouragement and for always pushing me farther than I thought I could go.

Dedication

To the almighty God, who is the ultimate source of positive energy and to my angel in heaven.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AD………………………………………………………………………………………….....Air-Dried
AEA………………………………………………………………………………Air-Entraining Admixture
CM ……………………………………………………………………………………..Control Mix
CRCA…………………………………………………….................Coarse Recycled Concrete Aggregates
CSA……………………………………………………………...............Canadian Standard Association
FRCA……………………………………………………..................Fine Recycled Concrete Aggregate
GGBFS………………………………………………………………Ground Granulated Blast Furnace Slag
GHG…………………………………………………………………………………...Greenhouse Gas
GP………………………………………………………………………………………Glass Pozzolan
GU……………………………………………………………………………...General Use Cement
GUL……………………………………………………….................General Use Limestone Cement
ICP…………………………………………………………………………...Interlocking Concrete Paver
IFSTTAR.................French Institute of Science and Technology for Transport Development and Networks
ITZ ……………………………………………………………………………Interfacial Transition Zone
LCA…………………………………………………………………...............Life Cycle Assessment
MJ………………………………………………………………………………..................Mega Joules
NA…………………………………………………………………………………...Natural Aggregate
NS.……………………………………………………………………………………...Natural Sand
OD ………………………………………………………………………………………….Oven Dried
PFA………………………………………………………………………………..Pulverized Fuel Ash
PPF……………………………………………………………………………….Polypropylene Fiber
RCA…………………………………………………………………………..Recycled Concrete Aggregate
RPM………………………………………………………………………………Revolutions Per Minute
SCM……………………………………………………………...Supplementary Cementitious Materials
SF………………………………………………………………………………................Silica Fumes
SSD…………………………………………………………………………....Saturated Surface Dried
TSMA………………………………………………………………………Two Stage Mixing Approach
WRA…………………………………………………………...............Water Reducing Admixture

Chapter 1
Introduction and Background

1.1 Introduction

The history of Interlocking Concrete Paver (ICP) is traced back to Roman times in the 19^{th} century. Stone was used as the main component in paving the roads and footpaths. These stone road pavements have served as the most prominent framework of a historical European city's material structure (Garilli et al. 2020). ICP has seen tremendous development since then, and a significant amount of research is still being carried out. The applications of ICP include sidewalks, driveways, crosswalks, parking lots, ports, and airports (Garilli et al. 2020). However, due to rapid urbanization and a growing population, it is critical to design urban roads in such a way that they can withstand heavy loads and respond to the public transportation system. High traffic volumes hasten pavement deterioration, prompting the development of durable pavements. Pavement, when deteriorated, needs repair and rehabilitation. The maintenance, repair, and rehabilitation of urban roads are extremely difficult due to their high volume and frequency of traffic, and keeping these roads closed for a long period can cause heavy economic implications (Garilli et al. 2020). The use of ICP can address most of the issues related to urban pavements. ICPs are produced in manufacturing facilities due to which the possibilities of material segregation and other defects that could be caused by pavements cast on-site are eliminated (Vaitkus et al. 2019). Furthermore, ICPs can be built in extreme weather conditions (cold & hot), so there is no seasonal limit for installing concrete pavers. Precast concrete pavers are manufactured in a controlled setting, resulting in more outstanding quality and more durable pavers than those cast on-site (Delatte, 2014). In general, rigid pavements need adequate time for curing to gain adequate strength. In contrast, prefabricated pavers can be installed at the site immediately and can be instantly opened to traffic (Delatte, 2014). Construction of ICP pavement does not require heavy construction equipment, and ICP offers ease of maintenance and low maintenance costs compared to the conventional pavement (Patel and Pitroda 2013). ICPs, when built properly, provide good results while requiring little maintenance and lowering costs for rehabilitation (Delatte, 2014).

Another critical issue in today's construction industry is natural resource depletion. Consumption of raw materials has become excessive due to population growth, intense industrialization, and the introduction of new technologies. Concrete is used in a variety of infrastructure applications, including buildings, roads, bridges, and tunnels. When these concrete structures reach the end of their service life or need to be replaced, they are demolished, and the waste is disposed of in landfills. Construction and

Demolition waste (C&D) is frequently a significant component, accounting for 20–30%, and in some cases more than 50%, of total municipal solid waste (Canada, 2021). The majority of C&D waste is made up of wood products, asphalt, drywall, concrete, and masonry. Putting this C&D to use could be an environmentally friendly and long-term solution.

Recycling concrete as aggregate for future concrete mixes has recently become a viable option for commercial concrete suppliers worldwide, particularly in Europe and North America (Paranavithana and Mohajerani 2006). RCA is a composite material composed of Natural Aggregate (NA) which has an adhered mortar layer coating and is produced by crushing large chunks of concrete into smaller chunks (Paranavithana and Mohajerani 2006). Concrete aggregate is a byproduct of the demolition of previously constructed infrastructure reclaimed, and the demolition rubble is then crushed and sieved to meet gradation standards. The use of RCA has elicited a variety of opinions due to the unpredictability and uncertainty of its origin. Another cause of concern for the widespread usage of RCA as a construction material is the lack of knowledge about what the source of RCA had previously been exposed (Gokce et al. 2004). Because of RCA's sustainability and economic benefits, many researchers have continued to study its effect on concrete properties.

Similarly, mineral admixtures have been used as Supplementary Cementitious Materials (SCMs) in portland cement concretes or as a component in blended cement. For every pound of cement produced, approximately 0.9 pounds of CO_2 are released into the atmosphere. Cement accounts for only a small portion of the constituents in concrete; producing a cubic yard of concrete (about 3900 lbs) results in the release of approximately 400 lbs of CO_2 (Association, 2020). SCMs used to partially replace cement are usually waste from the steel industry. The most commonly used SCMs are Fly Ash (FA), metakaolin, and Ground Granulated Blast Furnace Slag (GGBFS) (Kou, Poon, and Etxeberria 2014). Ground waste glass being used as SCM is also gaining acceptance. The use of SCMs can aid cement-based material construction in achieving sustainable development by lowering cement production and thus lowering fossil fuel consumption and Greenhouse Gas (GHG) emissions (Omran et al. 2018). SCM enhances concrete strength and durability by generating a denser matrix, prolonging the service life of concrete structures as a partial replacement for regular portland cement(Kou, Poon, and Agrela 2011). The addition of SCM to the concrete mixture is thought to have a beneficial impact. According to several research studies, the SCM improves RCA concrete's performance more than the NA concrete (Kou, Poon, and Agrela 2011).

Through proper research, using RCA and SCM as a partial replacement for NA and cement in ICP can be a more sustainable and economical way to produce ICP that can cater to the urban transportation system.

1.2 Research Gap

Extensive study on the structural design and construction of ICP is currently underway. There have also been studies on using RCA and SCMs as partial replacements for NA and cement in various structural elements. Furthermore, the performance of ICP with conventional materials has been extensively studied. However, there hasn't been much research into the performance of ICPs made of RCA and SCMs. If properly investigated, the use of RCA and SCM can produce a more sustainable ICP that performs equally as well as the conventional ICP that can also cater to the urban transportation system.

In collaboration with Sidewalk Labs, research was conducted to develop an ICP for the municipal application that can endure heavy traffic loads. An optimal paver design was chosen based on stress, deflection, and other significant factors (Omidi 2021). An equilateral hexagonal design, as shown in Figure 1-1 with a thickness of 200 mm, was adopted to integrate ICPs to cater to urban traffic. Maximum stresses in ICP under heavy loading were evaluated and determined using a finite element model (FEM) (Omidi 2021). However, laboratory testing was not conducted to confirm its performance.

Through the literature survey done in Chapter 2 of this thesis, the research gaps in the experimental investigation of shear stress behavior of ICP were revealed. Shear stress causes slippage along a plane or planes parallel to the imparted tension, and shear stress behavior is one of the most important elements determining ICP performance. Because ICPs are usually situated adjacent to each other for effective load transmission, researching shear behavior in ICPs is important.

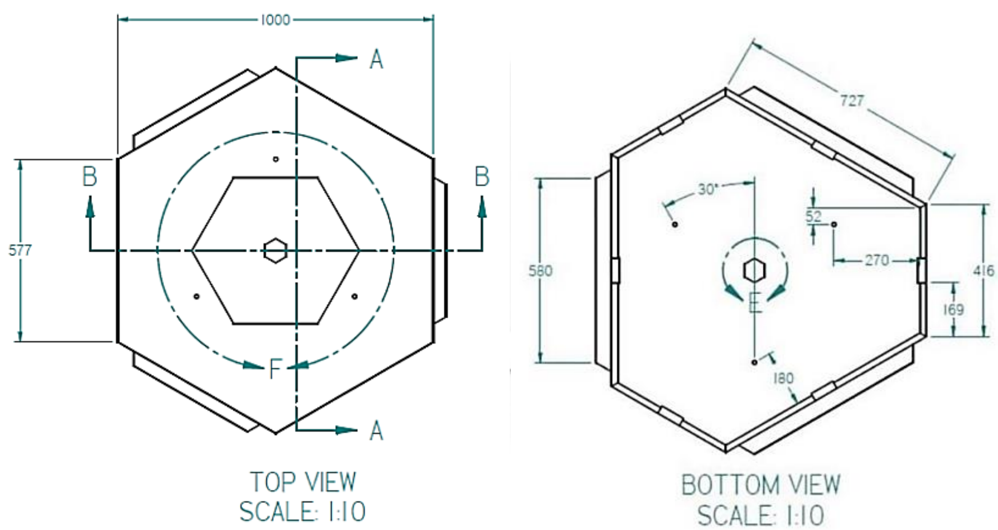


Figure 1-1 Top and bottom view of the concrete pavers (Omidi 2021)

1.3 Research Objectives

This study aims to compare the mechanical and durability performance of concrete mixtures with varying percentages of Coarse Recycled Concrete Aggregates (CRCA) and SCMs to that of conventional concrete mixes to produce ICP for its use in urban traffic.The concrete properties researched in this work include fresh properties such as slump and air content and hardened properties like compressive, shear, tensile strength, water absorption, and freeze-thaw durability. The compressive and shear strength values obtained from the laboratory investigation will be compared to the maximum stress values obtained from previous research (Omidi 2021) that utilized finite element modeling.

The use of RCA and SCM in structural elements has sparked considerable interest; however, using these materials in ICP has received less attention. This study, therefore, aims to promote the use of RCA and SCM as partial replacements for NA and cement in concrete mixtures to produce green and sustainable ICP.

1.4 Thesis Organization

This thesis is structured as per the University of Waterloo's general guidelines. It is arranged into five chapters.

- Chapter one introduces the research, and identifies the research gaps and research objectives.
- Chapter two presents a literature review on ICP, the materials used for this research, and experimental tests.
- Chapter three discusses the physical and chemical properties of the materials used for the research and the experimental program used for the study.
- Chapter four presents the test results and the necessary explanation regarding the results.
- Chapter five presents the conclusions and recommendations for future works.

Chapter 2
Literature Review

2.1 Interlocking Concrete Paver (ICP)

Interlocking concrete pavers are the modern-day solution for low-cost pavement. Paver blocks are pre-cast cement concrete paving units that are generally unreinforced and are used in the surface course of pavement (Patel and Pitroda 2013). The wearing surface of ICP is different than the conventional pavement types as it is composed of smaller paving elements that are bedded and jointed in the sand instead of continuous paving. The substructure beneath the bedding sand is comparable to that of a standard flexible pavement. Concrete block pavers are made out of materials used for rigid pavement, but the construction method used is that of a flexible pavement (Hasanan Bin Md Nor, 2006). The primary components of the load distribution in ICP are blocks consisting of concrete blocks arranged and connected with sand. The inability of an individual paver to move freely from another jointed paver is known as interlock and is classified into three major categories, that is horizontal, rotational, and vertical interlock (Barber, 1979). Interlock is critical to prevent horizontal movement of sidewalks when trafficked (Barber, 1979).

An ICP pavement is made up of concrete blocks or pavers placed on top of a layer of sand known as the bedding sand and acts like a flexible pavement (Beaty, 1992). The base layer of ICP is made of untreated, asphalt-treated, or cement-treated bases. A granular subbase layer is laid beneath the base layer if asphalt or cement-treated bases are used. The pavers are designed in such a way that a paver to paver joints can be laid alongside so that a frictional interlock is developed. Concrete pavers range from 200 to 250 mm in length and 100 to 112 mm in width. Depending on the volume of traffic, the thickness of the paver block is typically between 60 to 200 mm. Concrete pavers are typically installed on bedding sand of 20 to 40 mm thick which is separated by 2 to 4 mm sand joints (Chua, Askree, and Shackel 2000).

The pavers can be rectangular or one of over 200 specialized shapes. Paver shapes are classified into three types (Shackel.B, 1980). Dentate blocks that key into each other on all four faces make up Category A. Category B consists of dentated blocks that only key into each other on two faces. In contrast, category C consists of blocks that are not dentated and do not geometrically key together. The paver can be laid in several patterns. Herringbone, stretcher, basket weave, and parquet bonds are the most popular patterns. In a study, the performance of all the laying patterns was compared by using accelerated trafficking tests. Pavements with a herringbone bond pattern provided the best overall performance, whereas stretcher bond patterns had the most deformations (Shackel.B, 1980). The Herringbone pattern has three possible traffic-direction orientations, however, to withstand traffic shear stresses, it should be laid at 45° (Shackel.B, 1980).

There are now several methods for designing ICP pavements. The distribution of load and the modes of failure of ICP and flexible pavement is found to be alike, due to which many design approaches are modified versions of flexible pavement designs. However, several challenges remain, including inadequate categorization of the subgrade soil and paving materials, uncertainty surrounding pavement performance, and difficulty to specify desired pavement failure and reliability levels (Rada et al. 1991). Many factors influence the performance of ICP. The primary parameters that determine the performance of pavements include traffic, subgrade, base and subbase, bedding sand, jointing sand, edge restraint, paver shape, paver thickness, laying pattern, drainage, compaction, and strength (Shackel.B, 1980). All of these parameters must be considered when designing and constructing ICP pavement.

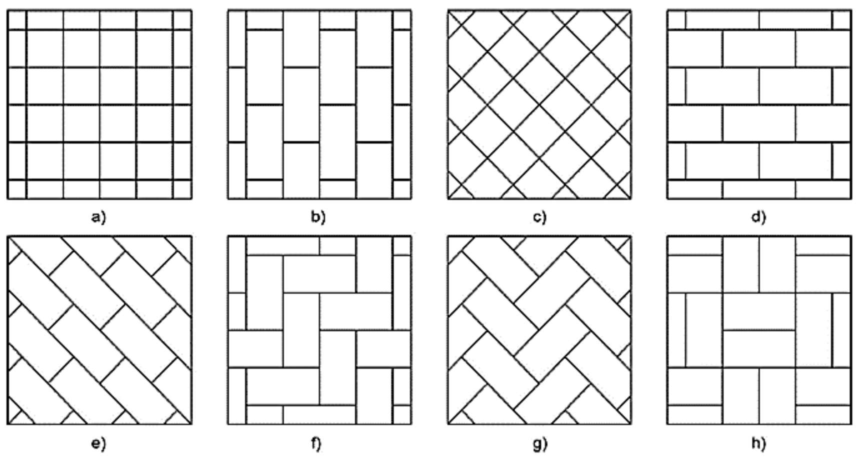


Figure 2-1Typical laying patterns used in ICP, a) stacked bond b) stretcher bond 90 ° or running bond, c) stacked bond 45° d) stretcher bond e) stretcher bond 45° f) herringbone 90° g) herringbone 45° and h) basketweave bond (Garilli et al. 2020).

2.2 Material

2.2.1 Recycled Concrete Aggregate (RCA)

The increasing population and advancements in technology creates demand for new infrastructure and place a massive burden on the environment in terms of natural resource requirement. On the other hand, the demolition of existing infrastructure creates a lot of demolition waste, which is often disposed of.

To address the issue of depletion of NA and demolition waste, RCA produced from C&D waste can be used to partially substitute the NA (Xiao 2018). The use of RCA is considered to be a more sustainable option (Oikonomou 2005). The general sources of RCA are new constructions, concrete plants, prefabrication plants, buildings, pavements, bridges, and disasters (earthquakes, avalanches, floods, etc.)(Gao et al. 2018; Xiao 2018). However, there are some other building wastes (wood, glass, plastic, metals, etc.) (Vivian W.Y. Tam, Soomro, and Evangelista 2018) and concrete waste that need to be eliminated from these contaminants. The quality and grading of RCA are obtained from several separating, screening, and crushing processes. Three crusher types (jaw, impact, and gyratory) are mainly used for recycling (Rao, Bhattacharyya, and Barai 2019). The Recycled Aggregate (RA) obtained from waste concrete is categorized into two types, CRCA and Fine Recycled Concrete Aggregate (FRCA) according to the particle size above or below 4.75mm (Xiao 2018). The FRCA negatively affects the concrete's mechanical properties and durability more than CRCA, as FRCA contains more porous materials (Bravo et al. 2018). The weakness of RCA compared with NA is from two additional components: old mortar and an Interfacial Transition Zone (ITZ) between the aggregate and the old mortar (Shi et al. 2016).

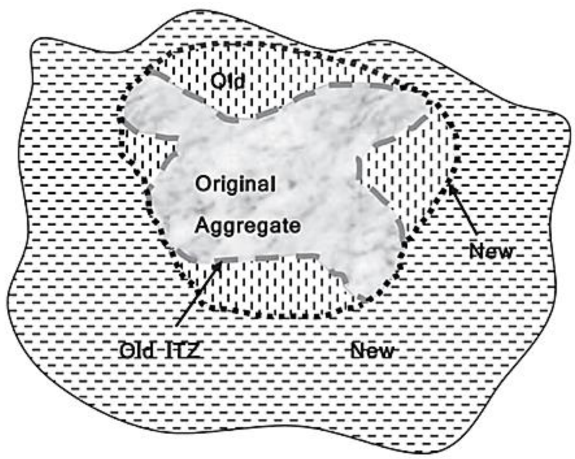


Figure 2-2 Formation of old and new ITZ in RAC (Kisku et al. 2017)

The mortar content that covers the RA surface is generally from the recycled source and crushing process, which leads to inferior aggregate properties, which results in lowered strength and density (Duan and Poon 2014).

RCA is considered a material that has a huge potential supply, one of the main issues with RCA is its inherent variability, as it depends on the source from which it is extracted. The variation in the RCA is caused by the variation in the concrete composition from which it is sourced. The intrinsic property of RCA is one of the main concerns which discourages its use in the construction industry. However, the use of RCA is now gaining acceptance as more research has been conducted in terms of its performance. Its use has been limited to non-cement-based applications (Vivian W Y Tam, Gao, and Tam 2005), as a granular base for pavements, as backfill materials, pavement shoulder construction, sub-base for pavements, and as fill material under the concrete slab.

RCA and NA have different physical properties. The physical properties that differ from NA are its shape, specific gravity, texture, bulk specific gravity, absorption, and pore volume. These properties in RCA are generally lower or worse when compared to NA; this is due to the extreme processing that RCA goes through which results in more angular and rough aggregates (Sagoe-Crentsil, Brown, and Taylor 2000). RCA also has higher pore volume and absorption value and lower specific gravity and bulk density. This can be attributed to the adhered mortar in RCA which is highly porous (Sagoe-Crentsil, Brown, and Taylor 2000).

RCA also exhibits very different mechanical properties when compared to NA. The values of aggregate abrasion, crushing, and impact are higher in RCA. These higher values indicate that the RCA generally has a weaker structure, and this is due to the adhered mortar layer. (Sagoe-Crentsil, Brown, and Taylor 2000). The mechanical properties of RCA are so much dependent on the quality of the adhered residual mortar layer (Chakradhara Rao 2018).

2.2.2 Supplementary Cementitious Materials

Concerns about environmental sustainability, as well as the causes and impacts of global warming, are ever-growing and have prompted the construction industry to seek out more sustainable building materials. Cement production as a binding material in concrete is energy-intensive. It is a cause of environmental concerns because 1 tonne of cement produces 1 tonne of CO_2 (5 to 8 % contribution to total global CO_2 emissions) (Krstic and Davalos 2019). The use of SCMs can aid cement-based material construction in achieving sustainable development by reducing cement production and, as a result, fossil fuel consumption and GHG emissions (Omran et al. 2018). The most used SCMs in concrete are fly ash and slag. The significant decrease in the availability of fly ash and the cost of slag has created a demand for an alternate source of SCM (Krstic and Davalos 2019). The SCMs reviewed for this research are Glass Puzzolans and Slag.

2.2.2.1 Glass Puzzolan

Glass is formed by liquefying silica, soda ash, and calcium carbonates ($CaCO_3$) at extreme temperatures after which it is cooled and this is when the solidification occurs without crystallization (Omran et al. 2018). Glass is considered to be amorphous (Omran et al. 2018). In many countries, post-consumption glass can be reused several times without significantly altering its physical and chemical properties (Singh and Singh 2019). Glass waste is typically discarded, and unrecycled glass generally ends up in landfills, causing obvious environmental issues. Glass powder that has been finely ground (38–45 µm) has potential use as an additional SCM in concrete. The glass powder has a high silica content, a large surface area, and an amorphous nature, implying that it could be used as SCM to replace cement in concrete. Its use would cut down on cement production, which is expensive and depletes natural resources (Singh and Singh 2019).

The Glass Pozzolan (GP) adds value by exhibiting pozzolanic activity which occurs when amorphous silica (SiO_2) in glass powder interacts with the portlandite [Ca(OH)2] produced in the course of cement hydration to form calcium silicate hydrate (C–S–H) gels (Shayan and Xu 2004). Omran et al. in their study suggest that because of its non-absorptive nature and smooth surface, the use of GP improves workability (Omran et al. 2018). Shao et al. studied the pozzolanic behavior and mechanical properties of concrete made with a 30% GP to replace cement with a particle size of 150, 75, and 38 µm (Shao et al. 2000). The compressive-strength values after 90 days revealed that the concrete made by using 30% glass powder of 38 µm particle size produced concrete whose compressive strength was 9% more than the conventional mixture. They concluded that finely ground glass powder has higher pozzolanic activity, resulting in higher concrete strength. Another study looked at properties like workability, compressive strength, and splitting tensile strength of concrete mixtures with varying percentages of cement substituted with waste glass powder. According to the findings, a concrete mixture with 21% waste glass powder improves the compressive strength; however, increasing the amount of glass powder in the concrete mixture decreases the workability and splitting tensile strength in concrete. (Olofinnade, Ndambuki, and Ede 2017). In a review by Singh et al. it was observed that generally, the results show that as the GP content in the mixtures increased, so did the resistance to chloride ion penetration (Singh and Singh 2019). Resistance increased over time because of the hydration of the cement and glass powder and also due to the improved pore structure in concrete. The results also show that replacing 10% of the cement with glass powder increases compressive strength by 4.53% at 7 days and by 3.7 % at 28 days of curing (Singh and Singh 2019). Split tensile strength results showed a 3.12 % and 4.69 % increment in strength at 7 days and 28 days in samples with a 5% replacement of cement with glass powder, respectively (Singh and Singh 2019). Furthermore, the influence of ground glass as a replacement for natural fine aggregates in concrete is investigated. The findings revealed that concrete's compressive strength and durability improved substantially (Oliveira 2008). Due to the improved pore network, the filling effect of GP particles, and the conversion of CH to C-S-H, the use of GP tends to improve the durability of concrete (Omran et al. 2018).

The results show that GP used to partially replace cement in concrete enhances the mechanical properties due to its pozzolanic activity. This type of concrete mixture can also potentially reduce GHG emissions (carbon dioxide emissions) associated with cement production while also protecting the environment.

2.2.2.2 Slag

Slag is a byproduct of steelmaking generated during the separation of molten steel from impurities in steelmaking furnaces. Efforts to utilize this type of industrial waste can aid in the creation of a more sustainable environment. Furthermore, storing slags in landfills harms the environment, not only because of the increased amount of land occupied by this type of waste but also because of the leaching issues it causes (Parron-Rubio et al. 2019).

Several studies were carried out toward investigating concrete mixtures containing various forms of slag in cement as one of its components. Parron-Rubio et al. in their study looked at the effect of several slag types by substituting 25% of the cement content in the concrete mixtures (Parron-Rubio et al. 2019). The obtained results revealed that the slag obtained from stainless steel reduced the water content without causing a significant reduction in the concrete strength. Another study by (Oner and Akyuz 2007) suggests that when the water-to-binder ratios of the mixes are considered, as the GGBFS content increases, the water-to-binder ratio decreases for the same workability, indicating that the GGBFS has a positive effect on workability. Furthermore, GGBFS used in mixtures outperformed the control mix. Parron-Rubio et al concluded that GGBFS is the most suitable for the production of sustainable concrete and as a substitute for cement, as it has been demonstrated to bring the same properties to the mixture as cement (Parron-Rubio et al. 2019).

Khatib et al. replaced up to 80% of cement with GGBFS using various substitutions (Khatib and Hibbert 2005). In substitutions up to 60%, good results were obtained, with compressive strengths comparable to traditional concrete. Oner et al. investigated the optimal level of GGBFS replacement on the compressive strength of concrete (Oner and Akyuz 2007). Their study suggested that the compressive strength of concrete increases as the GGBFS content increases until an optimum point is reached, after which the compressive strength decreases. The optimal level of GGBFS content for maximizing strength is identified as approximately 55-59% of total binder content (Oner and Akyuz 2007).

Cement substitution with slag is a good strategy for reducing cement consumption while addressing the waste management issue. Promising outcomes have been obtained.

2.2.3 Fiber

Concrete has high compressive strength but a ten-fold lower tensile strength. Furthermore, it exhibits brittle nature and does not permit the transfer of stresses after cracking (Blazy and Blazy 2021). Fibers are added to the concrete mix to prevent brittle failure and improve mechanical properties. In recent years, fibers in general, are popularly used in concrete, primarily to improve plain concrete's shrinkage cracking resistance, and toughness. Polypropylene Fiber (PPF) are fragments of oriented, extruded, or cut portions of polymer that are usually straight or deformed (Blazy and Blazy 2021). Microfibers and macrofibers are the two forms of PPF. They are distinguished primarily based on their lengths, but also on the role they fulfill in concrete (Blazy and Blazy 2021). Structural fibers are another name for macrofibers. Their length ranges from 30mm to 50 mm while the microfibers are smaller than 30 mm and are not used for load-bearing purposes (Blazy and Blazy 2021). PPFs are used in relatively small quantities.

Concrete with PPF does not show a significant improvement in compressive strength as it is primarily determined by the concrete matrix (Blazy and Blazy 2021). When the fiber content was increased from 0% to 0.30%, the compressive strength increased by 6%. In some studies (Chorzepa and Masud 2017; Mahdil et al. 2019; Tanyildizi 2009; Tavakoli et al. 2014), a decrease in compressive strength with increasing volume was observed. In other cases, (Ahmed, Ali, and Zidan 2020; Yap et al. 2014), the compressive strength improved until a particular threshold of fiber content was reached, after which it began to decline. The decrease in the strength could be due to lowered workability caused by an excess of fibers which also increases the content of the air in the concrete mixes (Gencel et al. 2011) and porosity (El-Newihy et al. 2018; Karahan and Atiş 2011; Ozawa et al. 2019). Aside from that, the fiber-aggregate interaction can influence the increase in air content (I. Markovic n.d.). The incorporation of PPF was seen to bring no significant effect on compressive strength. The tensile behavior of concrete with PPF is seen to be improved compared to concrete without fiber (Gencel et al. 2011; Ramesh, Gokulnath, and Kumar 2019; Said and Razak 2015; Siva Chidambaram and Agarwal 2015; Tavakoli et al. 2014; Wang et al. 2019). In a study (Saidani, Saraireh, and Gerges 2016), a 1% increase in micro PPF resulted in an 8% increase in splitting tensile strength, while a 4% increase in macro PPF resulted in a 65% increase. In another study, tensile strength improved from 5.27 MPa for reference concrete to 5.95, 6.10, and 6.30 MPa for concrete with 0.15, 0.30, and 0.45 percent micro PPF, respectively (Afroughsabet and Ozbakkaloglu 2015).

Bolat et al. found that the inclusion of PPF in concrete mix improved concrete durability by increasing the freeze-thaw resistance of concrete with PPF (Bolat et al. 2014). This is also supported by Zhang and Li's findings, which state that using PPF reduces freeze-thaw damage. It is claimed that this is due to the reduction in micro-cracks which makes it less likely for water to freeze (Zhang and Li 2013). In another study by Karahan and Atiş et al. (Karahan and Atiş 2011), the decrease in strength after undergoing several freeze-thaw cycles is lower for concrete containing PPF reinforcement than plain concrete. Similar findings are presented in another study (Pietrzak and Ulewicz 2018), where the compressive strength after a freeze-thaw test decreased by 20% for regular concrete, but only 8% for concrete with fibers, depending on the length of the fibers used. Furthermore, compared to the concrete with fiber reinforcement, a substantial loss of mass in the sample was witnessed during the freeze-thaw cycles of the conventional concrete.

The use of PPF is seen to enhance the mechanical and durability properties of concrete. Still, it is necessary to analyze the composition and properties of fibers to make sure that an adequate amount of fiber is used to avoid the negative effects.

2.3 Fresh Properties of Concrete containing RCA and SCM

2.3.1 Slump

The slump of fresh concrete is a measurement of the concrete's consistency. Generally, the ability of fresh concrete to flow is related to its consistency. Workability, on the other hand, is concerned with the placing and finishing of concrete and how successfully these operations may be carried out without compromising the homogeneity of the mixture.

RCA has a relatively high absorption potential. The absorption values of concrete containing RCA are higher than those of regular concrete (Kwan et al. 2012). This high absorption property of RCA tends to affect the workability of the concrete mixture. The value of the slump also depends on the method of mixing. A study found that the slump of concrete made using the standard mixing method was significantly higher than that of concrete made using the double mixing method (Poon and Chan 2007). In the double mixing method, half of the required water is mixed with aggregate to allow the water to freely penetrate the pores of the aggregate, lowering the initial free water content to lubricate the aggregate particles which results in a lower initial slump (Poon and Chan 2007). The conventional method required a longer time for the cement slurry with a higher viscosity than water to saturate into the aggregate pores, which gives rise to more initial free water to hydrate the aggregates. As a result, the conventional mixing method resulted in a higher slump. It was determined that concrete mixes made using the double mixing procedure retained their slump better than those made using the traditional mixing method (Poon and Chan 2007).

Poon et al. studied the effect of different moisture conditions on RCA and NA (Kou, Poon, and Etxeberria 2014). Before use, the aggregates' moisture states were controlled at Air-Dried (AD), Oven-Dried (OD), and Saturated Surface-Dried (SSD) states, and the cement-to-free-water ratio was kept constant for all mixes. The slump loss values of various concrete mixtures were determined, and the results revealed that the initial slump values of the concrete mixtures were dependent on the initial free water contents, and the slump loss values of the mixtures were related to the moisture states of the aggregates. Omran et al. in their study suggest that using puzzolan improves workability thereby improving the slump of the concrete mix due to its non-absorptive nature and smooth surface (Omran et al. 2018).

Water content, air content, size, shape, grading of aggregate, and presence of admixtures, are some of the major factors that influence the slump of concrete. All of these parameters must be kept constant to avoid any adverse results.

2.3.2 Air Content

Concrete's air content is a significant physical property. It indicates how much air is trapped or entrained within a batch of concrete. Generally, small voids are left in concrete after it has been placed and these voids are used to describe the trapped air in the concrete. Improper placement techniques can end in a higher level of entrapped air, lowering properties such as the compressive strength of the concrete. The addition of RCA to concretes has been found to increase the air content and cause greater variability in the values (ACI, 2004). Material properties rather than placement techniques cause this type of entrapped air (Ben Nakhi and Alhumoud 2019). The angularity, surface texture, and porosity of RCA form a means to entrain air (Ben Nakhi and Alhumoud 2019). Nakhi et al. in their study stated that because the bulk density of RCA is less than that of NA, the air content of concrete mixtures decreased linearly with an increase in RCA content (Ben Nakhi and Alhumoud 2019).

The air content of fresh concrete is therefore an important property and must be studied especially when using materials like RCA which has inferior properties when compared to NA.

2.4 Hardened Properties of Concrete containing RCA and SCM

2.4.1 Compressive strength

Concrete's compressive strength is an important material parameter typically linked to the concrete's quality. Since compressive strength tests can be carried out easily and other qualities of concrete mixtures are associated with it, it is often employed in material specifications. As a result, the implications of RCA addition on concrete's compressive strength have been included in the majority of RCA research.

A general trend shows that RCA affects the hardened properties in concrete. It has been observed that as the percentage of RCA increases, there is a decline in the hardened properties of the concrete. A study presented by Tiwari et al which uses the Indian standards to prepare cubes with 0%, 50 %, and 100% of Recycled Aggregates (RA), indicates a trend between the percentage of RCA replaced in a mix and its compressive strength (Tiwari and Nateriya 2016). Their results show that the increase in the replacement percentage of RCA in a concrete mix decreases the compressive strength. Another study presented by Kwan et al. also indicated the general trend between the percentage replacement of RCA and compressive strength. This study tested 100 x 100 x 100 mm cubes, which contained 15%, 30%, 60 %, and 80 % replacement percentages of RCA (Kwan et al. 2012). The results indicated a similar pattern: the compressive strength decreased as the percentage of RCA replaced increased. The results from this study can be seen in Figure 2-3

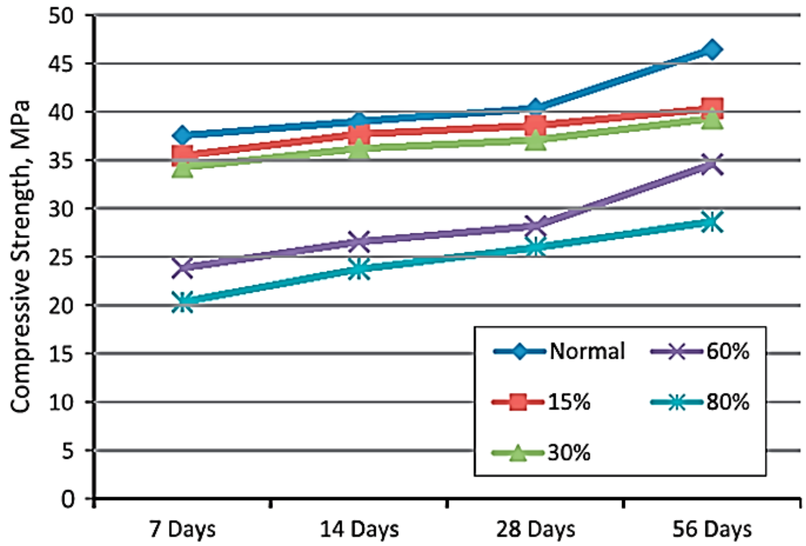


Figure 2-3 Average compressive strength of specimens with varying percentages of RCA at various curing periods. (Kwan et al. 2012)

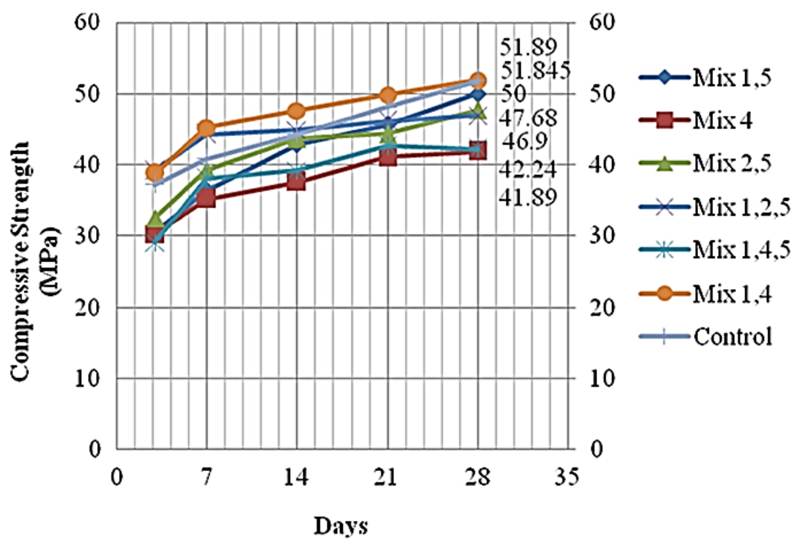


Figure 2-4 Development of compressive strength with time (Yehia et al. 2015)

A study conducted by Yehia et al. uses various grades of RCA, namely grade 1 (maximum size of 10 mm), grade 2 (maximum size of 25 mm), grade 4 (mixture of course and fine aggregate along with impurities), and grade 5 (fine sand) (Yehia et al. 2015). The samples were prepared by replacing 100% of

NA with RCA. The results, as shown in Figure 2-4 indicated that the mixes with grades 1, 2, and 5 depicted acceptable values of compressive strength due to the high packing density of the mix.

Additionally, Adetukasi et al examined concrete mixes with 25%, 50%, and 100% RCA replacement (Adetukasi 2020). All the mixes had the same water-to-cement ratio of 0.52. Their study also confirmed that increasing the percentage replacement of RCA lead to a decrease in compressive strength. This decrease in the compressive strength values is attributed to low specific gravity, high absorption value, and the presence of adhered mortar in the RCA. Emphasis is also placed on the weak interface between the adhered mortar and the original aggregate to decrease the compressive strength of the concrete mixes.

Some studies also show that RCA concrete can have a similar compressive strength to the concrete with NA. Research showed that RCA concrete had a lowered water-cement ratio and required more cement than the concrete from which the RCA originated to attain a comparable compressive strength (Padmini, Ramamurthy, and Mathews 2009).

In an experimental study, low-cement concrete in which cement was partially replaced with Fly Ash (FA), natural puzzolans, and electric furnace slags, as well as a 20% replacement of NA with RCA was studied. Dry and liquid consistency concrete mixes were developed and analyzed (Soldado et al. 2021). The parameters were compared to those of reference cement-based mixes. The results indicate that due to the pozzolanic effect, the compressive strength of mixes with additions increased further in 90 days compared to the values in 28 days. It is interesting to observe that given the reduction in cement, the strength increases up to 26% in the mix with FA and NA and up to 14% with FA and NA and RCA at 90 days when compared to the control mix (Soldado et al. 2021). The results reveal that a higher cement replacement (up to 50%) with specialized additions of FA, natural puzzolans, and slags combined with 20% RCA, results in better mechanical properties (Soldado et al. 2021).

The effects of RCA with and without Silica Fumes (SF), as well as GGBFS, on the physical and mechanical properties of concrete, are presented in a study by (Çakir 2014). It is observed that as the amount of RCA in the concrete increases, the compressive strength steadily decreases. At 28 days, the concrete strength at 100 % replacement level decreases by roughly 24%. The strength loss is more pronounced when the level of replacement is greater than 50% (Çakir 2014). It is also seen that the compressive strength for specimens with 100% RCA replacement and 5% and 10% SF content increases, while for the specimens with 100% RCA replacement and 30 % and 60 % GGBFS content the compressive strength declines (Çakir 2014). The higher values for mixes with SF are attributed to the particle size of SF, which is smaller than that of GGBFS; the filler effect of SF performed better than that of GGBFS (Çakir 2014). Another study used RCA in addition to pozzolanic materials (pulverized fuel ash (PFA) and GGFBS) to compensate for the loss of strength and durability caused by the use of RCA

(Ann et al. 2008). It was observed that the compressive strength of concrete containing RCA was lower than that of the control specimen at 7, 28, 90, and 180 days, but it was improved by substituting it with 30 %PFA and 65 % GGBS (Ann et al. 2008).

Generally, it is observed that the compressive strength of concrete mixes with RCA is affected by a higher percentage of replacement but it is improved with the addition of SCMs up to a certain limit.

2.4.2 Shear Strength

A material's shear strength is defined as its capacity to withstand forces that cause its internal structure to move against itself. Concrete's shear strength is dependent on aggregate qualities; they rely on aggregate interlocking to provide resistance to shearing stresses, and hence their shear behavior is significantly influenced by the use of RCA.

The shear behavior of RCA has been the subject of extensive research. However, the effects of RCA on concretes' shearing strength are not yet thoroughly understood (Rahal 2017). In an experiment, the shear strength of many specimens with RCA replacement ratios of 0%, 20%, 50%, and 100% were investigated. The values of shearing strength were shown to be highly dependent on the fraction of NA replaced with RCA. The data revealed that 20% and 50% replacement resulted in a 7% drop in normalized shear strength. Full replacement, on the other hand, resulted in a reduction of 29% (Rahal 2017). In another study, it was seen that shear strength and tensile strength increased first and then decreased with the increase in the RCA replacement ratio. The shear strength of RCA was slightly higher than that of the concrete with NA at a low replacement ratio. Results also indicated that the shear strength of RCA is directly related to the values of splitting tensile strength (B. Liu, Feng, and Deng 2019).

2.4.3 Splitting Tensile Strength

The splitting tensile strength test is a simple way to determine the strength of concrete under tension. This is done by placing a distributed load on the opposite edges of a cylinder. This results in a near-uniform tensile tension across the vertical plane, which is constrained on top and bottom by uniform compression loads (Pickel, 2014). Based on the load applied and the geometry of the specimen, the magnitude of this stress can be determined. The ultimate tensile stress is defined as the tension that causes the specimen to split.

Several studies have examined RCA's effects on the splitting tensile strength. The outcomes of these studies show that splitting tensile strength is less affected by RCA content than compressive strength (Mcneil and Kang 2013). When compared to concrete with NA, the values of splitting tensile strengths of concrete with 100% RCA are roughly 65% to 70% (Fonseca, Brito, and Evangelista 2011; Maruyama 2014; Padmini, Ramamurthy, and Mathews 2009).

According to Exteberria et al, while attached mortar in RCA produces a weak area for compressive failure, it can improve tensile strength in small quantities by generating a smoother transition between mortar and aggregate (Etxeberria et al. 2007). Studies targeted at enhancing the ITZ using specialized mixing techniques (Vivian W Y Tam, Gao, and Tam 2005), have observed that concretes' splitting tensile strength improved when the percentage replacement of aggregates was at lower levels. According to Yang et al, using an RCA source with a lower water/cement ratio and better overall strength is one way to improve the tensile strength of concrete incorporating RCA (Yang, Chung, and Ashour 2008). A study examined the effects of RCA with and without SF, as well as GGBFS, on the mechanical qualities of concrete (Çakir 2014). The RCA concrete's tensile splitting strength was found to be lower than the NA concrete's. The replacement of NA with RCA enhances the tensile splitting strength of SF-containing specimens. However, replacing the NA with RCA reduces the tensile splitting strength of GGBFS-containing specimens (Çakir 2014). To compensate for the loss of strength and durability induced by the use of RCA, RCA in combination with pozzolanic materials (PFA) and GGBS was utilized by Ann et al (Ann et al. 2008). It was seen that the use of PFA and GGBS or the pozzolanic material, in general, was less effective in increasing the tensile strength of specimens.

2.4.4 Water absorption

Water absorption of hardened concrete is an important component in determining concrete durability since water penetration is the leading source of steel corrosion and freeze-thaw damage. When dry specimens are submerged in water, water absorption is defined as the weight increase caused by absorbed water over the weight of the dry specimen due to capillary effects caused by high osmotic pressure (Kwan et al. 2012).

In a study by Kwan et al, five types of mixtures were prepared by replacing the NA with the RCA at 0%, 15%, 30%, 60%, and 80% of the total coarse aggregate content (Kwan et al. 2012). The absorption values of concrete containing RCA are higher than those of regular concrete, and the trend shows that with increased RCA content the absorption values increase (Kwan et al. 2012) (see Figure 2-5). As a result, only regular concrete and concrete with 30% or less RCA content were designated as low water absorption concrete. Concrete with 80 % RCA replacement seemed to have the highest absorption value, 2.2 times greater than the typical value. The increase in the absorption value is attributed to the RCA's high absorption capacity, which resulted in a higher osmotic pressure within the concrete.In another study, the influence of CRCA and cement-based cementitious materials on the durability of concrete was explored experimentally (Bao et al. 2020). To make the concrete with RCA a water-to-binder ratio of 0.33

and 0.39 was maintained, two types of RCAs were obtained, and several substitutions of RCAs ranging from 0% to 30%, 50%, and 100% by weight were chosen. Concrete samples were exposed to pure water and a 3% NaCl solution, and the amount of absorbed capillary water was measured. The initial coefficient of capillary absorption was observed to increase as the replacement ratio of RCAs increased, but it decreased when the better quality of RCAs was used. The physical features of RCA, as well as the influence of attached mortar, are strongly linked to the absorption values in RCA concrete.

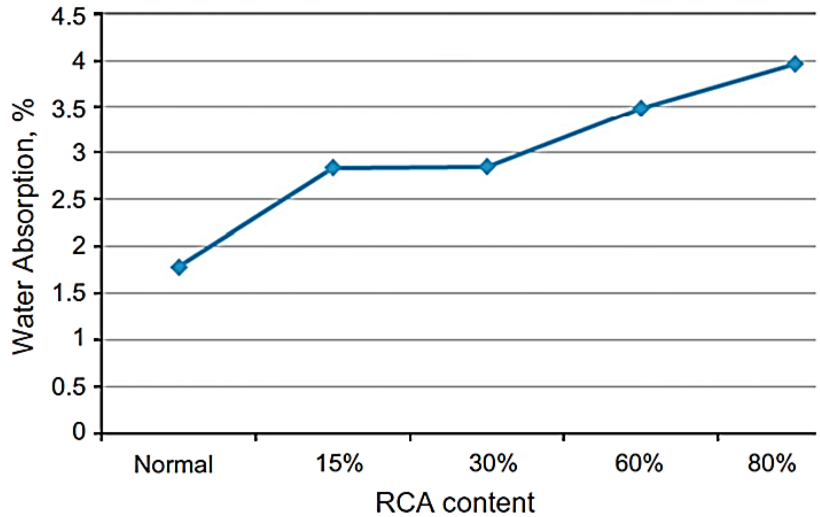


Figure 2-5 Percentage of Water absorption for concrete mix with varying percentages of RCA (Kwan et al. 2012)

In a study, the values of water absorption in concrete with a higher content of fly ash (FA) addition (50 % of cement replacement rate) are found to be similar to that of the reference. Concrete with a 30% FA replacement rate has even better results, as its water absorption value is 44% less than the conventional mix (Soldado et al. 2021). The use of RCA is advantageous because it has equal or lower capillarity values than combinations made entirely of natural materials. FA helps reduce water penetration resulting in 65 % lower water absorption values than the conventional concrete mix, and RCA does not affect this parameter (Soldado et al. 2021). The density and the water absorption ratio have an inverse relationship in RCA concretes as seen in an experimental investigation by (Çakir 2014), where concrete compositions with RCA replacement from 25% to 100% are explored. This relationship is more significant where larger amounts of NA are replaced by RCA content.

2.4.5 Freeze-Thaw Durability

Certain materials, like concrete, can endure the highly damaging forces of cyclic freezing and thawing, known as freeze-thaw resistance. Water is the most important component in the freeze-thaw cycle. When water freezes and expands at low temperatures, it exerts enormous pressure on the pores of the concrete causing multiple cracks and thereby affecting the durability of concrete. Concrete is a composite material with varying thermal properties due to its constituent materials. Because aggregate makes up the majority of concrete, the thermal properties of the aggregate have a significant impact on the concrete's behavior. RCAs have a higher absorption capacity than NAs due to which they are more vulnerable to freeze and thaw effects.

Impurities in RCA reduce concrete's resistance to aggressive environments (Poon and Chan 2007). These impurities increase porosity and the likelihood of chemical attack (Ann et al. 2008). In their study, Xiao et al reviewed a series of literature and found that the strength loss rate of concrete with RCA is higher than that of NA concrete, owing to the RCA's lower freeze-thaw resistance due to its higher water absorption (Xiao 2018). It was concluded that the freeze-thaw resistance of RCA concrete decreases as the RCA replacement percentage and water-cement ratio increase. Still, it increases when fly ash and air entertainment agent are added to the RCA concrete mixes (Xiao 2018). Because of its porous nature, RCA is more susceptible to freeze-thaw cycles or harsh climates. Any unsound particle within the RCA that deteriorates due to constant freeze-thaw cycles would allow water to enter the surrounding cement paste and cause frost damage (Zaharieva 2004). Hwang et al also mentioned the RCA concrete's susceptibility (Hwang et al. 2013). Another research investigates the freeze-thaw durability of RCA concrete using a paired comparison test based on weight loss and final compressive strength. It concludes that using air entrainment and polypropylene fibers in RCA concrete is equally effective for providing freeze-thaw durability when compared to concrete made with virgin aggregates with air entrainment and polypropylene fibers (Richardson, Coventry, and Bacon 2011). According to Gokce et al, the durability of RCA concrete is affected by the source of the original concrete. They discovered that RCA concrete made with air-entrained RCA outperformed RCA concrete made with non-air-entrained RCA (Gokce et al. 2004).

Jain et al researched the scaling resistance of concrete containing Type C fly ash and incorporated RCA up to a 100 % replacement (Jain et al. 2012). These specimens were subjected to 50 freeze-thaw cycles in a 4% $CaCl_2$ solution. It was concluded that the specimens containing RCA performed well and experienced scaling comparable to the control specimen. They attributed the RCA scaling resistance to an efficient air void system (Jain et al. 2012).

2.4.6 Sustainability

There are several biodiversity benefits to using RCA and SCMs. The use of RCA reduces the demand for NA, whose production requires quarrying and can harm the ecosystem. The use of RCA has the potential to significantly reduce the demand for NA, which is an incremental benefit. Using RCA also reduces the amount of waste concrete disposed of in landfills, reducing the need for such industries and, as a result, the overall footprint. The use of SCMs also has several advantages: it reduces landfill waste and the demand for conventional cement, and thus reduces CO_2 emissions, which benefits the ecosystem considerably.

This study also utilizes general use limestone cement (GUL), which contains 11.3 % less clinker component replaced by limestone. Compared to conventional cement, GUL-type cement emits less greenhouse gas due to lower clinker content, and this reduction in greenhouse gas emission results in less impact on the ecosystem.

2.4.6.1 Life Cycle Assessment

The Life cycle assessment (LCA) framework is adopted to quantify the environmental performance of the mix designs in Table 2-1. The LCA methodological framework generally includes four steps defined by the ISO 14040 standard.

An assessment was conducted as a preliminary evaluation which aimed to determine the sustainability performance of alternative materials for concrete mixtures in the production of ICP. The assessment was completed first for $1m^3$ of the mix designs, followed by the functional unit of 1km for a two-lane (7m) pavement section (Achebe J. C., 2021).

The environmental factors considered in the study are the use of energy resources and the impact of climate change. Energy consumption and CO_2 emissions pollution were assessed during material production, material transportation, and pavement construction. The environmental performance of each mixture and the impact of changes in material proportions and technology were determined in comparison to conventional materials for concrete pavement. A system boundary was drawn at the construction site to define the scope using a cradle-to-gate LCA approach (Achebe J. , 2020).

A life cycle inventory assessment was performed during which all the material and energy inflows into the system, as well as the emissions to air, water, and land, were identified and accounted for. This assessment focused on the energy used in the various processes and the CO_2 emitted at all stages considered within the system boundary. Because energy use and emission data for some materials considered in the mix designs in Table 2-1 were not available in the Athena pavement LCA database, a simplified assessment was conducted using data from the Athena database and other available sources found in the literature (Achebe J. C., 2021).

The density of the mixtures and the transportation distance for the material proportions in each mixture were the two main assumptions made in this analysis. All mixtures were assumed to have the same density and the same mass of each mixture would be reduced per volume of the pavement section investigated. Material transportation is typically regarded as the primary source of environmental impacts when considering the use of recycled materials. For this analysis, a similar transportation distance (30 km) for all recycled materials and aggregate, and a transportation distance of 50 km for ordinary Portland cement (GU) and limestone Portland cement (GUL) were considered (Achebe J. , 2020).

2.4.6.2 Concrete Mixture Development

According to a previous study at CPATT, 12 concrete mixtures, including the control mix, were recommended for the production of ICP, while keeping mechanical performance and applicability in the Canadian context in mind (Achebe J. C., 2021). Under several tests, mixtures with varying percentages of SCM and CRCA outperformed the conventional mixture. GP, FA, GGBFS, and GUL cement are used to partially or completely replace General Use (GU) cement; CRCA is used to partially replace coarse aggregate (Achebe J. C., 2021).

The mix proportions and the material quantities were adopted from the French Institute of Science and Technology for Transport, Development, and Networks (IFSTTAR) documents for mix design, based on existing research founded by the IFSTTAR (Achebe J. C., 2021). Material quantities per meter cube served as the foundation for estimation of the required quantity of materials for all concrete mixtures proposed in this study. This mix proportion is used for the sustainability assessment, laboratory testing, and development of the overall mix design (Achebe J. C., 2021)

Table 2-1 Primary mix design for 1m3 of concrete mixture (Achebe J. C., 2021)

Concrete Mixtures	GU	Coarse Aggregate	Fine Aggregate	Water	Steel	GUL	GP 10%	Slag 20%	FA 10%	CRCA 25%
1. Control Mix, GU 100%)	417	950	793	188	40	0	0	0	0	0
2. GUL 100%	0	950	793	188	40	417	0	0	0	0
3. 90%GU + 10% GP	375.3	950	793	188	40	0	41.7	0	0	0
4. 80%GU + 20% slag	333.6	950	793	188	40	0	0	83.4	0	0
5. 70%GU +20% slag+10% GP	291.9	950	793	188	40	0	41.7	83.4	0	0
6. 80% GU +10%FA+10%GP	333.6	950	793	188	40	0	41.7	0	41.7	0
7. 100GU + 75%NA + 25% CRCA	417	712.5	793	188	40	0	0	0	0	237.5
8. 90%GUL + 10% GP	0	950	793	188	40	375.3	41.7	0	0	0
9. 80%GUL + 20% slag	0	950	793	188	40	333.6	0	83.4	0	0
10. 70%GUL +20% slag+10% GP	0	950	793	188	40	291.9	41.7	83.4	0	0
11. 80% GUL +10%FA+10%GP	0	950	793	188	40	333.6	41.7	0	41.7	0
12. 100%GUL + 75%NA + 25% CRCA	0	712.5	793	188	40	417	0	0	0	237.5

2.4.6.3 Life Cycle Assessment Results

The assessment measured energy use in Mega Joules (MJ) and CO_2 pollutants in Kg CO_2 equivalent as indicators of resource use and climate change impact, respectively (Achebe J. , 2020). The following section contains the results and interpretations obtained from this study.

2.4.6.3.1 Impact of Materials

As seen in Figure 2-6 , it depicts the energy use demand for pavement built with the concrete mix design listed in Table 2-1 (Achebe J. C., 2021).

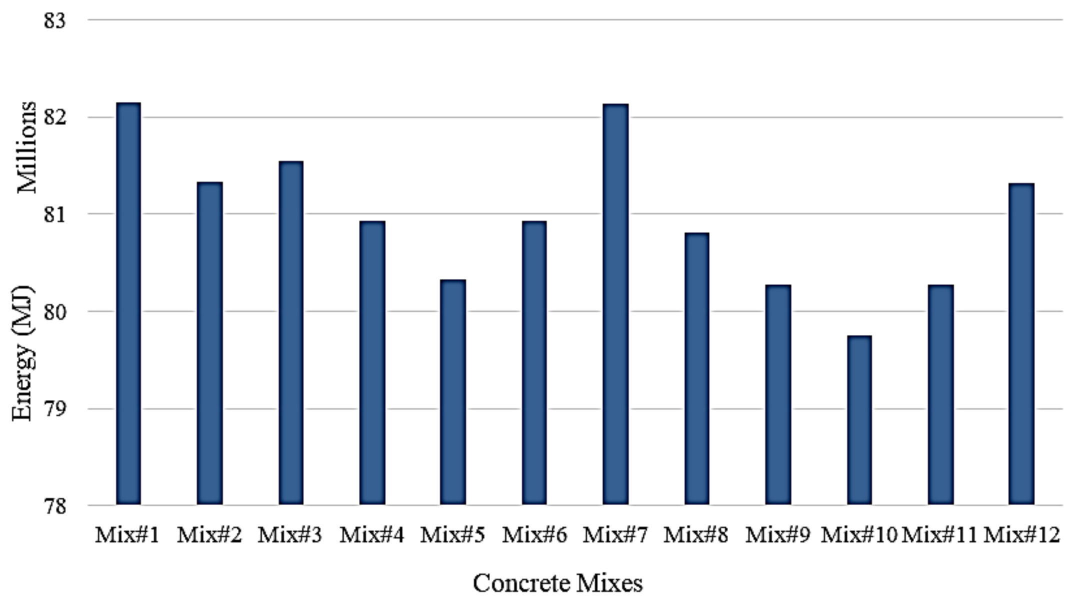


Figure 2-6 Energy use impact from cradle to gate for construction of 1 km pavement with 2 lanes of 3.5m each using mix designs with varying proportions of RCA and SCMs in the surface layer (Achebe J. C., 2021)

This represents the total amount of energy expended to produce material, transportation from the manufacturing facility to the construction area, and pavement construction on site. In terms of energy use, Mix 10 provides the greatest environmental benefit. When compared to the Control Mix, all mixtures had a lower energy demand, but Mix 7 performed the worst. The energy savings of Mix 10 is because it uses GUL cement and a higher percentage of SCM (30%), which has a lower requirement in terms of energy in material production than the conventional cement (Achebe J. C., 2021).

Table 2-2 Energy use for all concrete mixtures for constructing 1km for 2 lanes (3.5m each) pavement

Concrete Mixtures	Energy Use		
	Material Production	Material Transport	Equipment
1. Control Mix, GU 100%)	10.4%	0.2%	89.4%
2. GUL 100%	9.5%	0.2%	90.3%
3. 90%GU + 10% GP	9.7%	0.2%	90.0%
4. 80%GU + 20% slag	9.1%	0.2%	90.7%
5. 70%GU +20% slag+10% GP	8.4%	0.2%	91.4%
6. 80% GU +10%FA+10%GP	9.1%	0.2%	90.7%
7. 100GU + 75%NA + 25% CRCA	10.4%	0.2%	89.4%
8. 90%GUL + 10% GP	8.9%	0.2%	90.9%
9. 80%GUL + 20% slag	8.3%	0.2%	91.5%
10. 70%GUL +20% slag+10% GP	7.7%	0.2%	92.1%
11. 80% GUL +10%FA+10%GP	8.3%	0.2%	91.5%
12. 100%GUL + 75%NA + 25% CRCA	9.5%	0.2%	90.3%

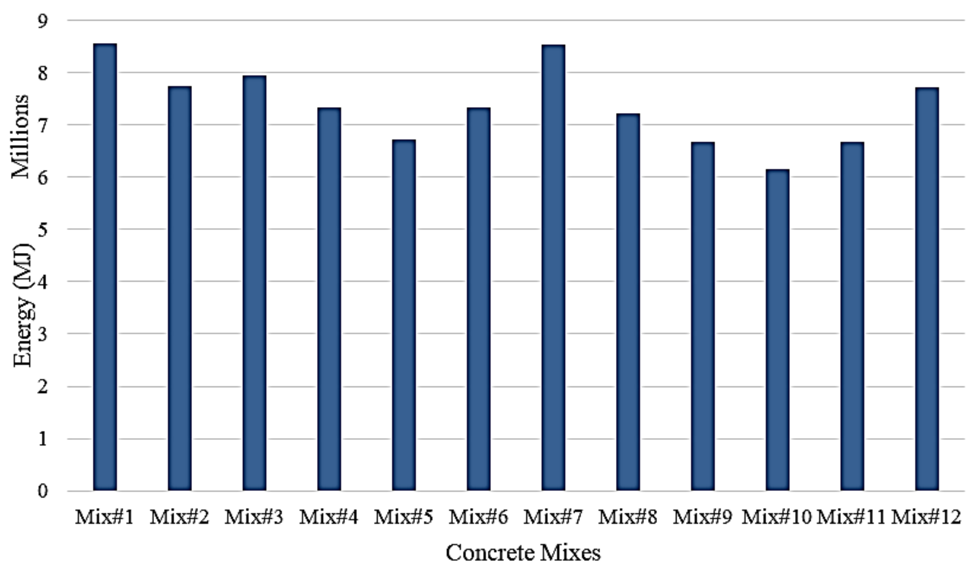


Figure 2-7 Use of energy for material production of mix designs with varying proportions of RCA and SCMs (Achebe J. C., 2021).

Although Mix 7 contains RCA, the energy demand to process RCA before its use in the concrete mixture causes it to generate the greatest impact on the environment in terms of energy resource use when compared to other mixtures.

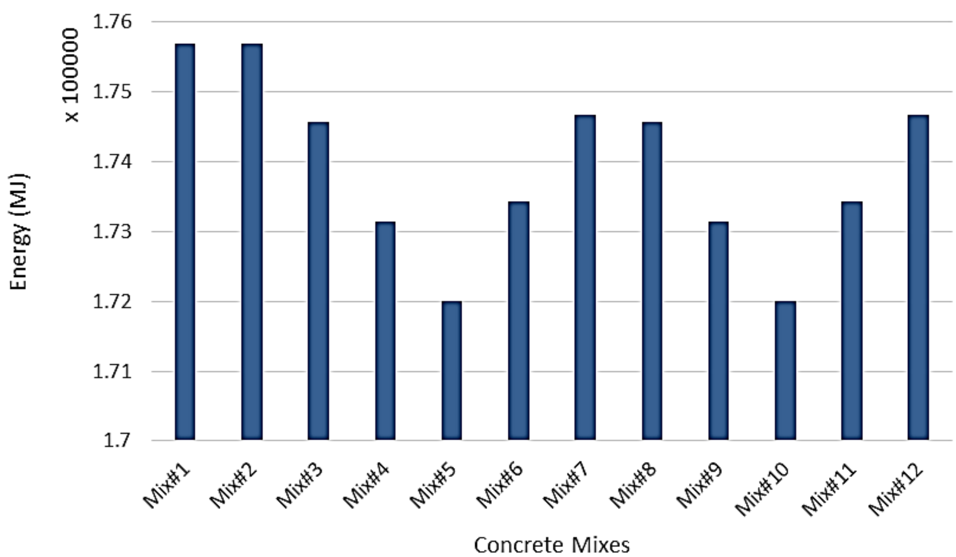


Figure 2-8 Material transportation energy use of mix designs with varying proportions of RCA and SCMs (Achebe J. C., 2021).

Although the energy used by construction equipment contributed the most to the LCA energy demand of all mixtures, there was no difference between them because the same construction techniques and conditions were assumed in this study. However, when considering the cradle-to-gate impact of these mix designs, the contribution of the construction stage to the total energy use impact was not equal, as shown in Table 2-2. This outcome reflects the impact of various energy demands during material production and transportation (Achebe J. C., 2021).

The findings for material production mirror those of the total impact, with Mix 10 providing the maximum benefit and Mix 7 having the lowest impact as shown in Figure 2-7 (Achebe J. C., 2021). Similarly, as illustrated in Figure 2-8, the performance ranking of concrete mixtures is apparent in the demand for energy for the transportation of material (Achebe J. C., 2021).

When the production of 1m^3 of a concrete mixture is considered, the consequence of producing the materials and the benefit of transportation can be illustrated, as shown in Figure 2-9 and Figure 2-10

(Achebe J. C., 2021). When compared to the CM, Mix 10 uses over 30% less energy whereas Mix 7 has just under 5% energy saving in comparison to the CM (Achebe J. C., 2021).

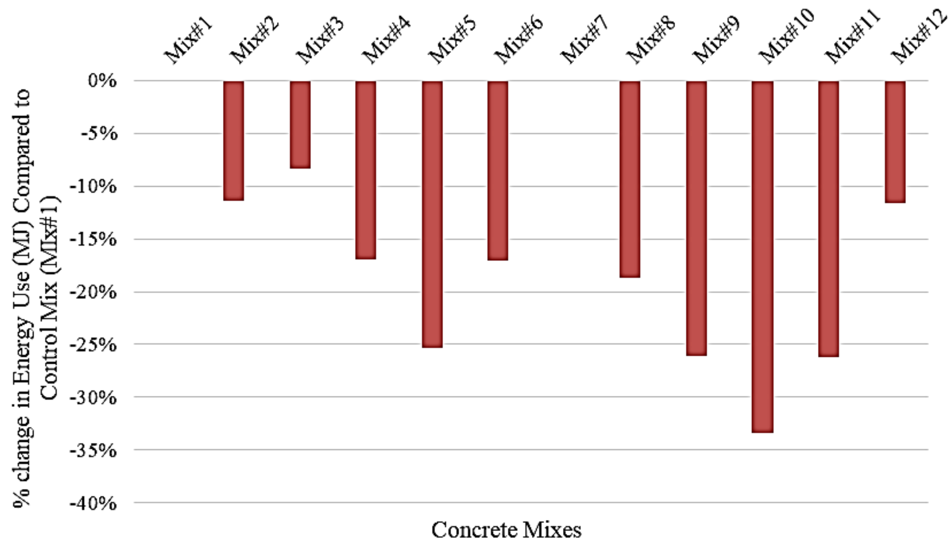


Figure 2-9 Percentage of material production energy use savings of all mixtures (Mix 2 – Mix 12) compared to CM (Achebe J. C., 2021).

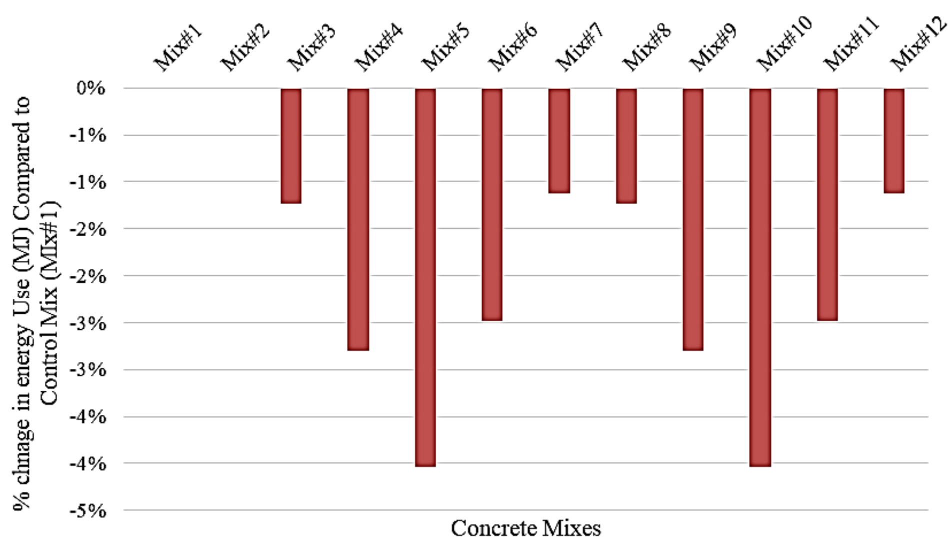


Figure 2-10 Percentage of material transportation energy use savings of all mixes (Mix 2 – Mix 12) compared to CM (Achebe J. C., 2021).

Again, in terms of impact due to climate change, all of the mix designs outperformed the CM, as illustrated in Figure 2 12. Mix 10 had the greatest Figure 2 10decline, whereas Mix 7 had the minimum decline in comparison to Mix 1 (Achebe J. C., 2021). Figure 2 13 illustrates the effect of material production on climate change, while Figure 2 14 depicts the effect of material transportation from manufacturing plants to construction sites (Achebe J. C., 2021)Figure 2 15 and Figure 2 16 show the percentage reduction in CO2 emissions for all alternative mix designs compared to the Control Mix when comparing the impacts of material production and transportation for 1m3 of the mix.

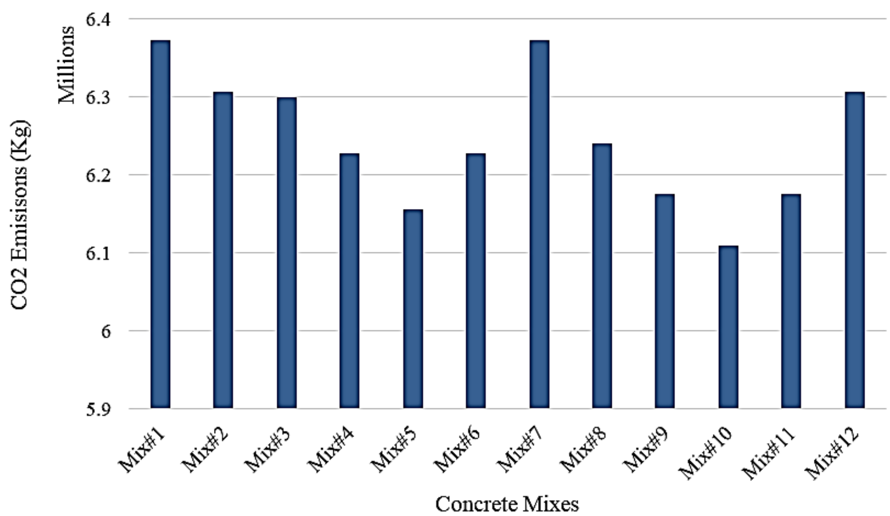


Figure 2-11 Cradle to gate climate change impact of mix designs with varying proportions of RCA and SCMs (Achebe J. C., 2021).

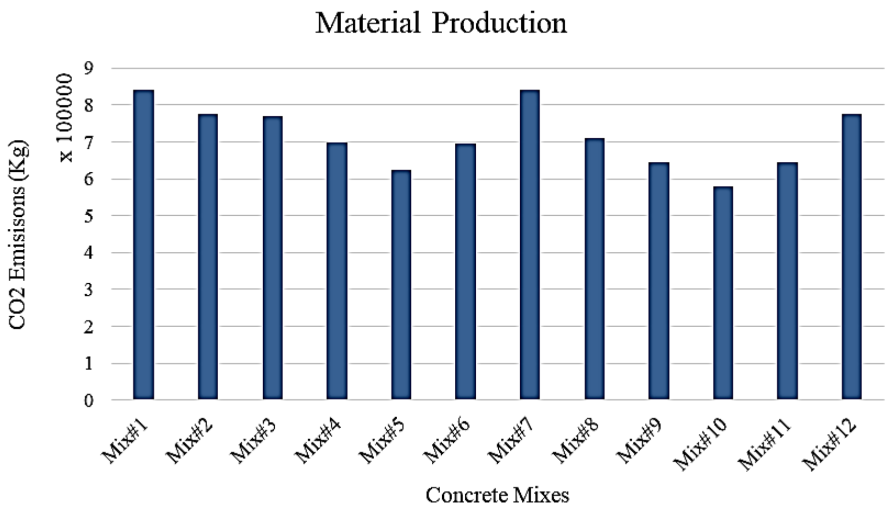


Figure 2-12 Impact of climate change on material production of mix designs with varying proportions of RCA and SCMs (Achebe J. C., 2021).

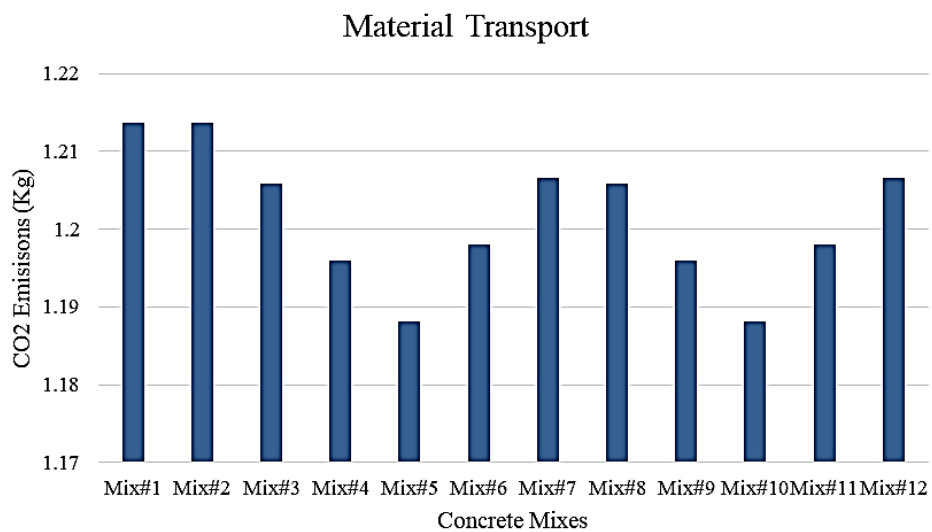


Figure 2-13 Impact on climate change due to material transportation of mix designs with varying proportions of RCA and SCMs (Achebe J. C., 2021).

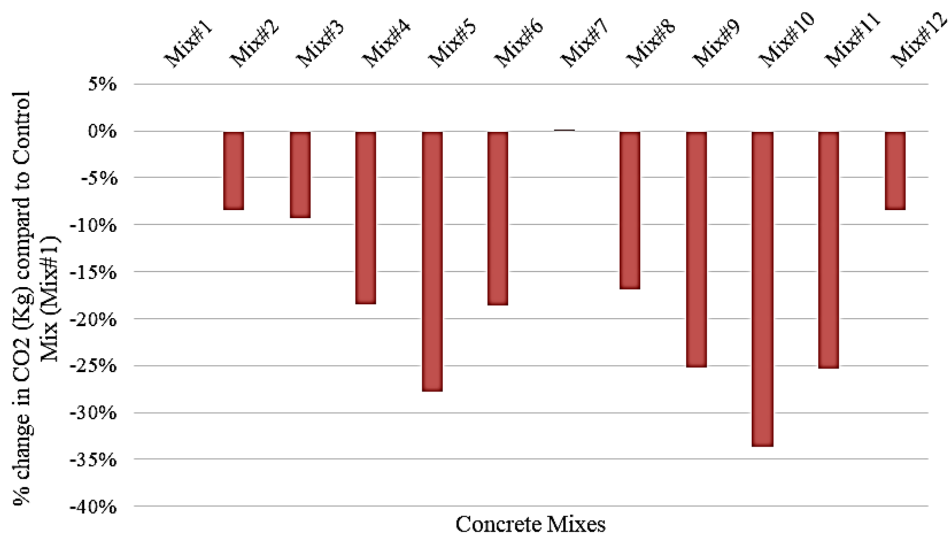


Figure 2-14 Percentage reduction in CO_2 emissions from material transportation for all mixtures (Mix 2 – Mix 12) compared to the CM (Achebe J. C., 2021).

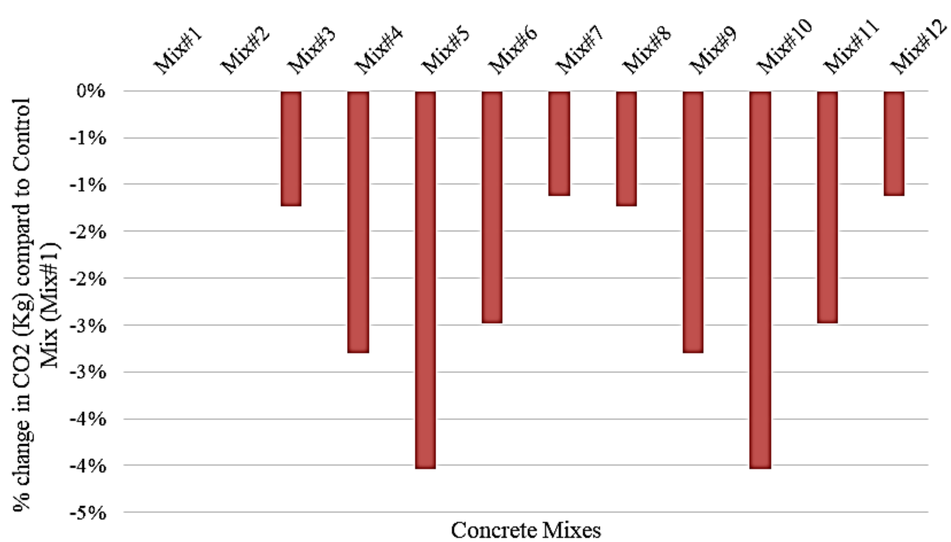


Figure 2-15 Percentage reduction in CO2 emissions from material transportation for all mixtures (Mix 2 – Mix 12) compared to the CM (Achebe J. C., 2021).

2.4.6.4 Selected Mixtures

The use of RCA had no effect on energy use or CO_2 emissions when compared to Mix 1 (GU 100%) and Mix 7 (100 % GU + 75 % NA + 25 % CRCA) or Mix 2 (GUL 100 percent) and Mix 12 (100 %

GUL + 75 % NA + 25 % CRCA). The reduction in all four RCA mixtures was solely due to GUL replacing GU in Mix 2 and Mix 12.

Table 2-3 Selected Mixtures for Laboratory Testing

Concrete Mixture	Natural Aggregate (%)	Recycled Concrete Aggregates (%)	GUL (%)	Slag (%)	GP (%)
Control Mix	100	0	100	0	0
Mix 1	80	20	100	0	0
Mix 2	100	0	80	20	0
Mix 3	100	0	70	20	10
Mix 4	100	0	90	0	10
Mix 5	80	20	70	20	10
Mix 6	80	20	80	20	0
Mix 7	80	20	90	0	10
Mix 8	60	40	70	20	10

Furthermore, based on the practical standpoint of sustainable material availability, it was recommended that variants of selected mixtures (Mix 8, Mix 9, and Mix 10) with RCA replacement be developed and tested in the laboratory. This resulted in the addition of five (5) additional mixtures to the selected mixtures. As shown in Table 2-3, eight (8) mixtures were chosen for laboratory testing, in addition to a Control Mix containing 100 percent GUL.

2.5 Summary

From the literature review, it is observed that the use of RCA is limited mostly as fill type material. It is also observed that a lot of research has been done on the mechanical and durability performance of concretes with varying percentages of RCA replacement.

The quality, size, and shape of RCA, water content, air entrainment, as well as the presence of any admixtures, are seen to influence the slump of concrete. The compressive strength of concrete mixes with RCA from the literature generally decreases with the increasing percentage of replacement. However, the loss in this strength was seen to be improved by adding SCMs to the concrete mixes. Mixes with RCA replacement up to 30% in addition to SCMs seemed to provide adequate strength. It was also observed that extensive research has been conducted on the shear behavior of RCA. However, the effects of RCA on concrete shear strength are not fully understood. Generally, the shear strength is also seen to decrease with the increase in the percentage of RCA in the concrete mix and the addition of SCMs does not have any significant effect on the shear strength values. Similarly, the tensile strength of RCA concrete mixes decreased as the percentage of RCA increased; however, these values were however less affected when compared to the compressive strength values. Adequate tensile strength values were achieved at lower aggregate replacement levels and the addition of SCMs was seen to be less effective in enhancing these values. The absorption and resistance of concrete mixes to free-thaw were reviewed, and it was seen that RCA in the concrete resulted in higher absorption values and lowered resistance to freeze and thaw. However, the addition of SCMs to the concrete mixes along with RCA was seen to positively impact the absorption and freeze-thaw resistance values due to its pore-filling properties and efficient air void system.

The Life cycle assessment revealed that the energy use benefit in concrete mixtures was generally due to the use of a high percentage of SCMs and the GUL cement, as they have a lower demand for energy during production when compared to GU cement. It was also seen that the energy needed to process the CRCA before its use in the concrete mixture had the most significant environmental impact regarding energy resource use. The use of CRCA did not affect energy consumption or CO_2 emissions. The reduction in CRCA mixtures was solely due to GUL replacing GU cement.

These contributions help promote the potential use of RCA and SCMs not only as a fill material but also in the structural members. This literature review also guides us to a view that using RCA and SCMs would provide adequate mechanical and durability properties for ICP concrete pavers which will be further studied in this research.

Chapter 3
Materials and Research Methodology

3.1 Research Methodology

The research methodology used for this study is depicted in Figure 3-1 below. This chapter focuses on each of the components depicted in the figure in detail. The study is divided into four major parts: aggregate tests, concrete batching, casting, and curing of fresh concrete properties, and hardened concrete properties.

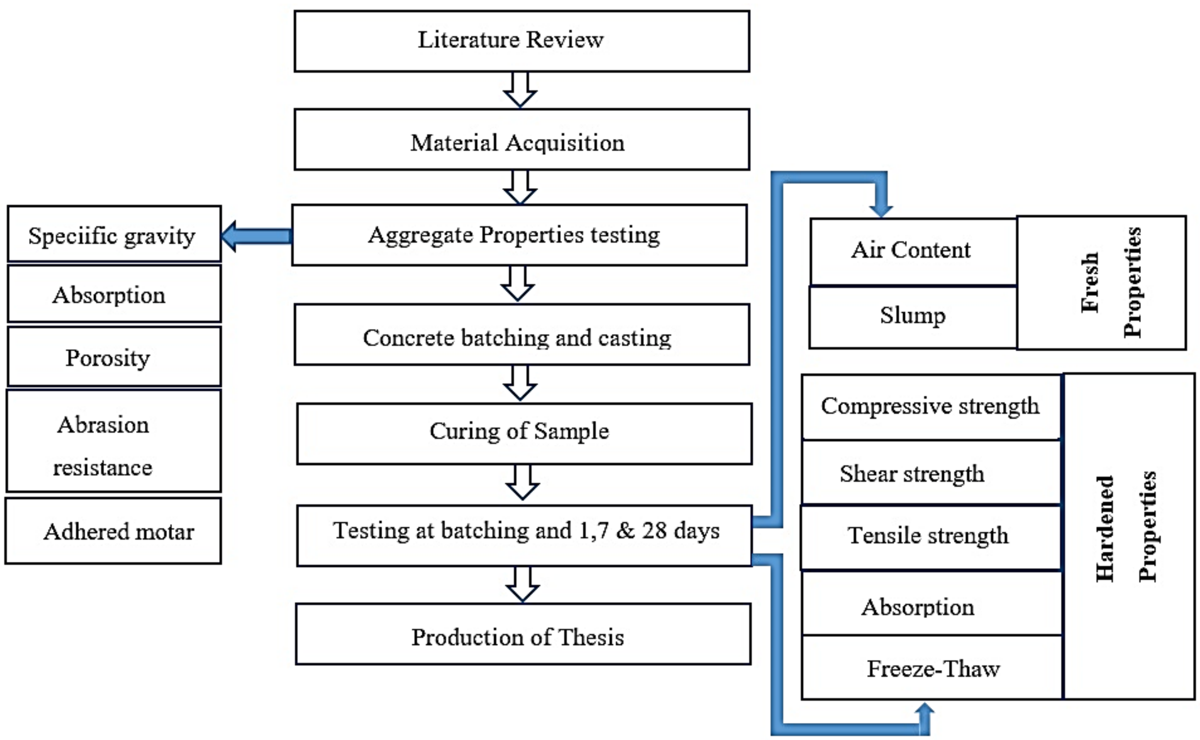


Figure 3-1 Research methodology implemented for this study

3.2 Materials

3.2.1 Coarse Aggregate

3.2.1.1 Gradation

3.2.1.1.1 Natural Coarse Aggregate

Figure 3-2 Natural Aggregate used in this study

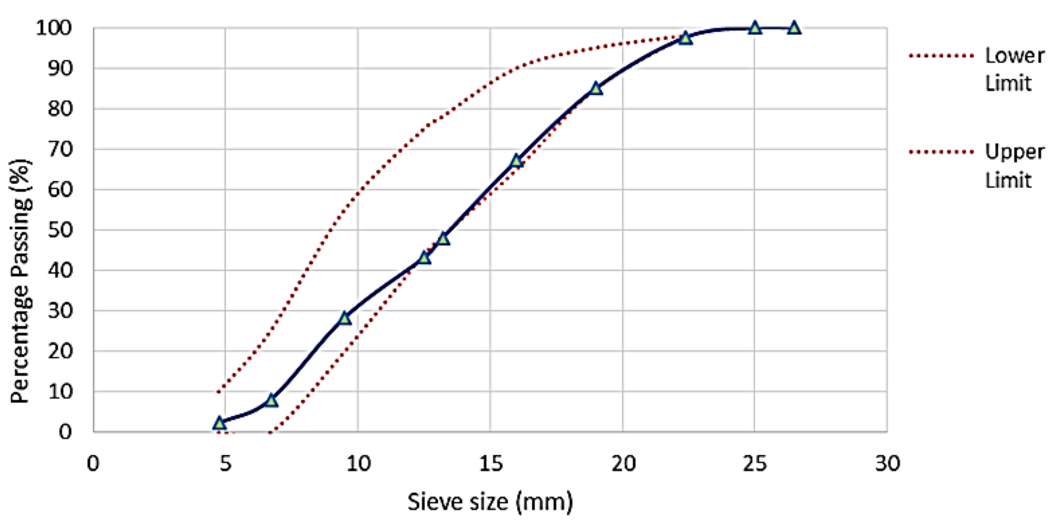


Figure 3-3 Particle size distribution for Natural aggregates

Natural coarse aggregates used for this study comply with (CSA A231.1/A231.2 2006) and were supplied by the Miller group. The particle shape of the aggregates was irregular/rounded and had a smooth/rough surface texture as shown in Figure 3-2. All aggregates' gradation was according to

Canadian standard association (CSA) A23.1-2009 with 19 mm nominal size. The gradations can be seen in Figure 3-3 and the aggregate properties can be seen in Table 4-1.

3.2.1.1.2 Coarse Recycled Concrete Aggregate (CRCA)

The RCA used in this study was obtained from a concrete plant and was produced by crushing concrete with undesirable properties, performance, and age (Al-Bayati, 2019). Compared to FRCA, CRCA tend to have a smaller proportion of attached mortar (Sánchez, Juan, and Alaejos 2009). As a result, the use of CRCA is expected to be more successful than FRCA due to its higher-quality properties. The current study is primarily on the CRCA fraction of the RCA, due to the aforementioned factors. The CRCA used in this study is the portion of RCA that managed to retain on the sieves ranging between 4.75 mm and 19mm (Al-Bayati, 2019). The materials were thoroughly washed to remove as much adhered mortar as possible before being oven-dried at 110°± 5° C and graded using a mechanical shaker following LS-602 (MTO, 2001). Gradations of CRCA can be seen in Figure 3-5, and the dashed curves represent the acceptance level set by LS-602 (MTO, 2001). It can be seen that the gradation of CRCA falls within the defined envelope and can be used in concrete in terms of its gradation. The aggregate properties of CRCA can be seen in Table 4-1.

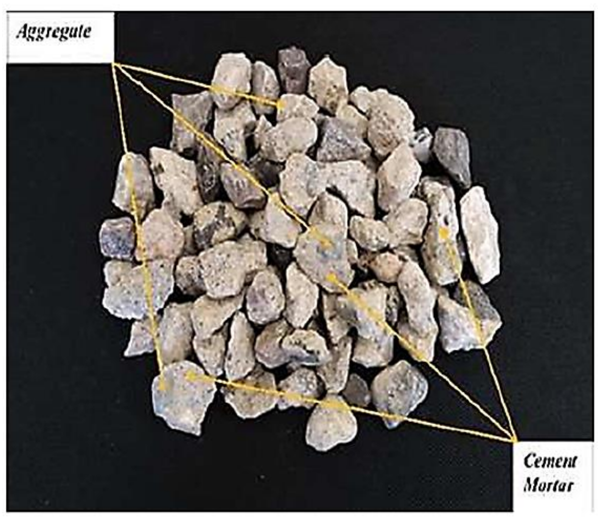


Figure 3-4 Coarse Recycled Concrete Aggregate (CRCA) used in the study

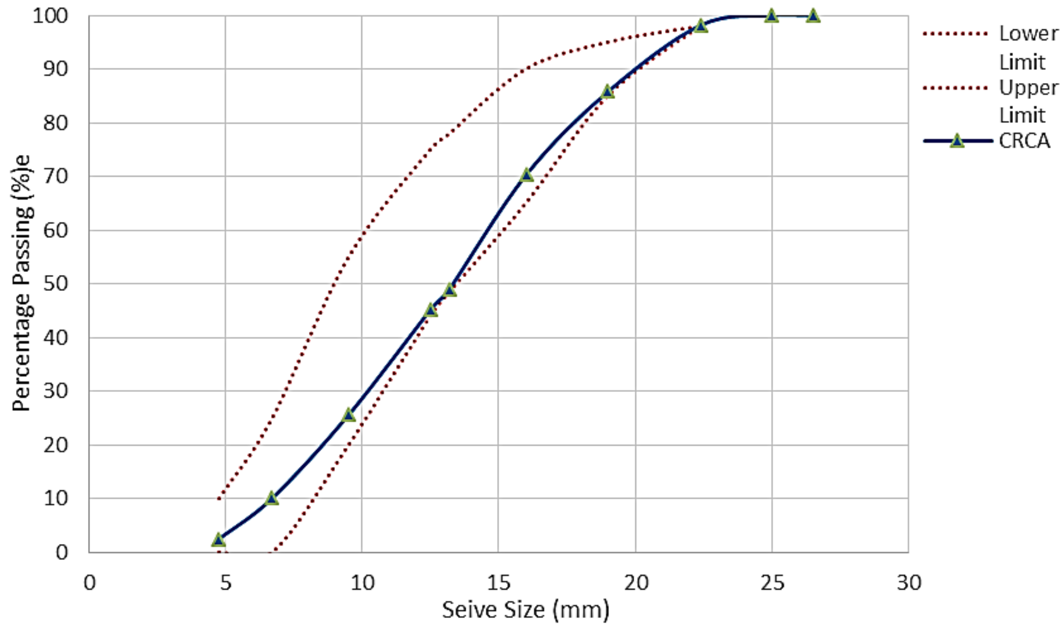


Figure 3-5 Particle size distribution for Coarse Recycled Aggregate (CRCA)

3.2.1.1.3 Fine Aggregates

Natural sand (NS) was used as fine aggregate for casting all the concrete mixes in this study and was supplied by the Miller group from Aurora concrete plant. This fine aggregate is considered high-quality concrete sand and is used in commercial concrete in Ontario. The gradation of fine aggregate can be seen in Figure 3-7.

Figure 3-6 Fine aggregates used in this study

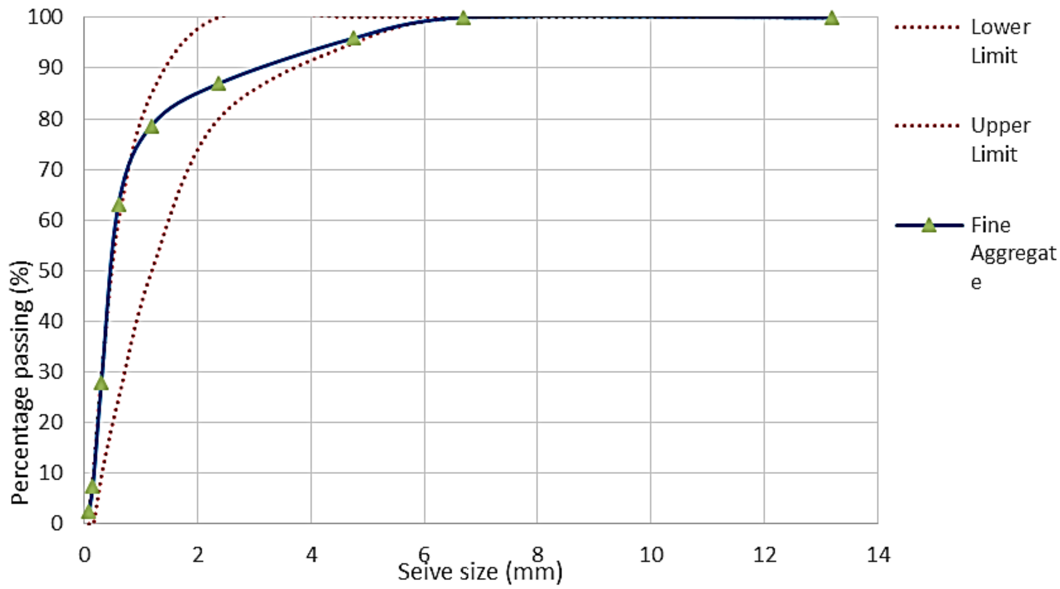


Figure 3-7 Particle size distribution for fine aggregate

3.2.2 Cementing Materials

All of the mixes used general use limestone cement (GUL) with 11.3% limestone powder content that met the requirements of the CAN/CSA-A3001 standard (CSA 2019). GGBFS (Ground Granulated Blast Furnace Slag) was used as SCM to replace a percentage of cement. Another SCM that was used as a partial replacement for cement was glass puzzolan (GP). The chemical make of all the cementing materials used in this study can be seen in Table 3-1.

a.

b.

c.

Figure 3-8 (a) Ground granulated blast furnace slag (b) Ground glass puzzolan and (c) General use limestone cement used in the study

Table 3-1 Chemical analysis of cementing materials

Cementing Material	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)
GeneralUse LimestoneCement (GUL)	63.4	18.9	4.4	3.2	0.7	2.7	0.12	_
GGBFS	38.5	40.1	7.8	0.74	9.7	2.21	0.38	0.53
GP	10.9	71	1.82	0.61	0.94	<0.1	13	0.52

3.2.3 Micro Synthetic Fiber

Table 3-2 Physical properties of micro synthetic fiber

Physical Properties	Values
Specific Gravity	0.91
Melting Point	160°C
Ignition Point	590 °C
Absorption	-
Alkali Resistance	Excellent
Electrical Conductivity	Low
Thermal Conductivity	Low
Tensile Strength	415 MPa
Modulus of Elasticity	5.52 Gpa
Length	19 mm
Aspect Ratio	29

A micro synthetic fiber that met ASTM C 1116 requirements was used as reinforcement in the concrete mixes. The use of micro synthetic fibers in concrete inhibits and controls the formation of plastic and drying shrinkage cracking. It also increases toughness, impact resistance, surface abrasion resistance, as well as long-term durability. The physical properties of the micro synthetic fiber used in this study are shown below in Table 3-2.

Figure 3-9 Micro synthetic fibre used in this study

3.2.4 Chemical Admixtures

a. b.

Figure 3-10 (a) Air entraining and (b) water-reducing admixtures used in this study

As per ASTM C260, BASF Micro-Air was used as an air-entraining admixture (AEA) in all mixes. AEA is required when producing concrete exposed to extreme climatic conditions, which becomes essential, especially in regions like Canada. All mixes contained BASF Pozzolith 100 XR as a water-reducing admixture (WRA).

3.3 Aggregate Properties

3.3.1 Specific Gravity and Absorption

The apparent and bulk-specific gravity, and the absorption, of coarse NA and RCA, are measured as per the ASTM C127 test procedure. Approximately 3 kilograms (kg) of aggregate were dried in the oven before the test and were 19 mm in size. The aggregate was sieved using a 4.75 mm sieve to remove any passing material. The sample was then soaked in water for 24 hours at room temperature before towel drying it to eliminate any moisture on its surface and confirm that the aggregate had attained a saturated surface dry state (SSD). The material was then weighed and was noted as “B”. The sample aggregate was immersed in water in a basket at a temperature of 23 ± 2.0°C, then weighed in water and the weight was noted as "C." The sample was taken out of the water and oven-dried at 110 ± 5.0 °C before being air-cooled for 1 to 3 hours to attain room temperature. The dried sample was weighed and denoted as "A."

The values of specific gravity were calculated using the following equations:

$$Relative\ density\ (Specific\ gravity\ (oven\ dry)) = \frac{A}{(B-C)} \ldots\ldots. (3\text{-}1)$$

$$Apparent\ Specific\ gravity = \frac{A}{(A-C)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3\text{-}2)$$

$$Relative\ density\ (Specific\ gravity(SSD)) = \frac{B}{(B-C)} \ldots\ldots\ldots.. (3\text{-}3)$$

$$Absorption, \% = \frac{(B-A)}{A} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3\text{-}4)$$

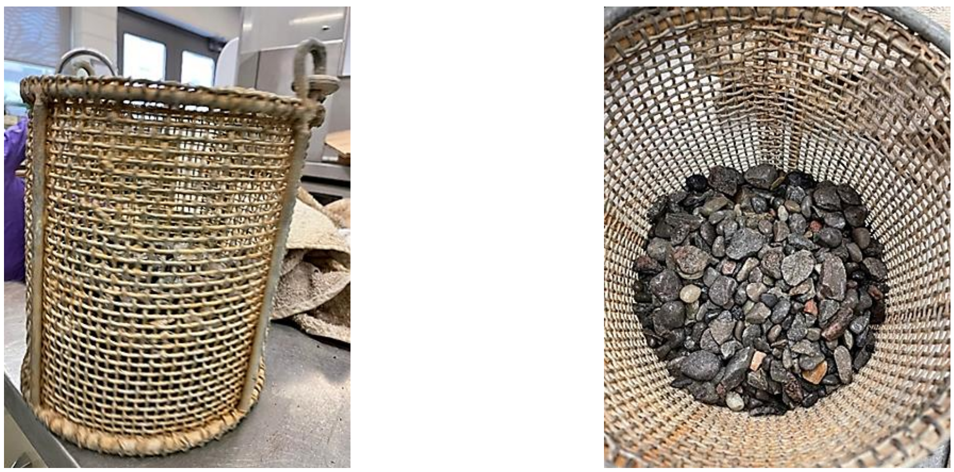


Figure 3-11 Aggregates in surface saturated dry state

Figure 3-12 Aggregates in a basket for specific gravity test

3.3.2 Abrasion Resistance

The Micro-Deval technique is employed to understand the aggregates' (both course NA and RCA) resistance to abrasion. According to ASTM D 6928-10, this technique is used to assess the aggregate's resistance to abrasion under moisture conditions. The Micro-Deval test is carried out as follows, and the apparatus used is depicted in Figure 3-14.

Passing, mm	Retained, mm	Mass, g
19.0	16.0	375
16.0	12.5	375
12.5	9.5	750

Figure 3-13 ASTM D 6928 standard required weight of aggregate for Micro-Deval test according to gradation

The Micro-Deval abrasion loss is obtained from the equation given below:

$$Micro - Deval\ Percent\ Loss\ = \frac{(A-B)}{A} \times 100 \quad \text{.................. (3-6)}$$

Figure 3-14 Micro - Deval apparatus

As shown in Figure 3-13 about 1500 ± 5 grams of oven-dry aggregate, 19mm in size, was taken and its weight was recorded as "A" and graded following the ASTM D 6928 standard. Before conducting the test, the sample was immersed in 2.0 ± 0.05 liters of water at 20 ± 5°C for a minimum of 1 hour. As shown in Figure 3-15, the sample along with soaking water and 5000 ± 5 g of steel balls was transferred to the vessel and placed inside the testing apparatus. Upon closing the lid on the vessel, the machine was run at 100 revolutions per minute (RPM) for 2 hours. The aggregates were then removed from the machine and transferred through 4.75 and 1.18 mm sieves, after which the steel balls were retrieved with the help of a magnetic rod. The aggregate that was retained on the 4.75 mm and 1.18 mm sieves was then dried at a temperature of 110 °± 5° C, after which the weight of the sample was recorded as "B".

Figure 3-15 Steel balls being separated from aggregates using magnetic rod after Micro-Deval abrasion test

3.3.3 Analysis of Adhered Mortar Loss

Due to the lack of standard test methods or specifications for measuring the amount of adhered mortar, a method developed in a study by Ismail and Ramili et al. was used in this study (Ismail and Ramli 2013). The following procedure was carried out to determine the amount of adhered mortar.

500 g of oven-dried CRCA was used and was noted as "M_1" in this test. The sample was tested in the Micro-Deval apparatus firstly with the steel balls after which the steel balls were removed and the sample was tested without the steel balls for 15 minutes each. After thoroughly washing the sample, it was sieved through a 4.75 mm sieve to make sure that the finer material passed through and only the coarse aggregate remained. The sample was then oven-dried at 105°C, for 24 hours and weighed, and noted as “M_2”.

The loss of adhered mortar for CRCA is obtained from the equation below:

$$Adhered\ Mortar\ Loss\ Percent, \% = \frac{M_1 - M_2}{M_1} \quad \text{(3-7)}$$

3.4 Fresh Concrete Tests

3.4.1 Batching

The batching procedure followed the two-stage mixing approach (TSMA) (V. W.Y. Tam, Gao, and Tam 2006). First, the fine aggregates were added to the concrete mixer drum as shown in Figure 3-16. All cementitious materials, including SCMs, were added and manually mixed. The coarse aggregates were then added, followed by half of the mixing water, and mixed to initiate the aggregate coating. The AE and WR admixtures were also added along with the water. The remaining water was then added and mixed until the fresh concrete became homogeneous.

Figure 3-16 Concrete mixers used in the production of concrete

Because this was the only mixer accessible throughout the study, and its capacity was insufficient to accommodate the number of concrete mixtures required owing to a large number of specimens, each batch of the concrete mixture had to be divided into two halves to guarantee correct mixing. To make sure that the batching process was consistent for all mixtures the following procedure was used:

1. Cement, fine aggregates, and SCMs were added to the mixer and mixed manually for proper mixing.
2. Coarse aggregate and half of the mixing water and AE and WR admixtures were then added and mixed for 60 seconds.

3. The remaining water was added, and the mixture was mixed for 3 minutes, then rested for 60 seconds and mixed further for 60 seconds before continuing with the fresh property testing and sample preparation.

3.4.2 Slump

The slump of the fresh concrete is measured as per the procedures defined in CSA A23.2-5C (Canadian Standards Association 2019). The mold used for the testing was a standard cone whose top diameter was 100 mm and bottom diameter was 200 mm with a height of 300 mm.

Three equal volumes of fresh concrete were placed in the damp mold. This test employed a 16 mm diameter steel tamping rod with a rounded end. The surface of each layer of concrete was applied with 25 blows. When the last layer of concrete was poured, it was rodded and the surface was then leveled. After the surface layer was leveled, the cone was lifted vertically, which allowed the concrete mixture to slump. The cone was then turned over and placed alongside the slump of the concrete mixture to serve as a reference for measuring the vertical displacement of the concrete. The average value of the three measurements accounted for the top layer's differential settlement. Figure 3-17 shows the procedure for measuring the slump of a fresh concrete sample.

Figure 3-17 Measurement of the slump in fresh concrete

3.4.3 Air Content

The air content in the concrete mixtures is determined using the method defined in CSA A23.2-4C (Canadian Standards Association 2019) . The concrete was placed in a pressure vessel and consolidated. The pressure vessel used in this study as shown in Figure 3-18, was cylindrical, with an internal diameter of 206mm and a height of about 212 mm approximately.

The concrete mixture was placed in approximately three equal layers and rodded; after rodding, each layer was compacted with a mallet to ensure that the majority of trapped air bubbles were removed from the concrete mixture. After that, the container was filled, and the surface was leveled. The lid of the cylinder was secured to the container in an air-tight manner. Any voids remaining between the concrete surface and the vessel lid were filled with water. The vessel was then filled with air at a standardized pressure. The air which penetrated through the concrete mixture indicated the concrete's air content. The values of air content were then recorded.

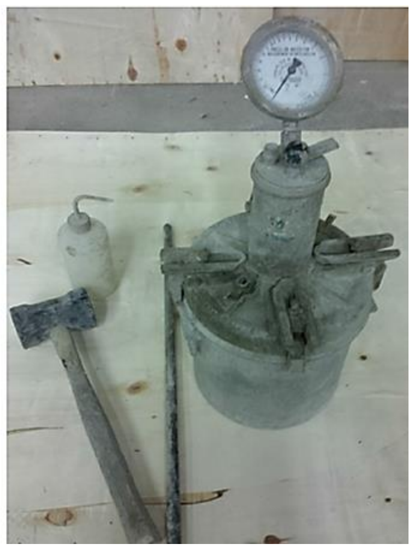


Figure 3-18 Air meter and other apparatus for testing air content

3.5 Harden Concrete Tests

3.5.1 Compressive Strength Testing

The compressive strength tests were performed according to CSA A.231(CSA A231.1/A231.2 2006). Each mixture was tested for compressive strength using 100 x 200 mm concrete cylinders at 1, 7, and 28 days. The tests were performed on the compressive strength testing machine. Figure 3-19 illustrates a sample under compressive pressure.

The machine consisted of upper and lower bearing blocks, the lower bearing blocks moved vertically to apply load to the specimens. All results were recorded and presented as an average of three test specimens. All specimens were made in such a way that they had a flat surface that allowed for the ends to be in plane with approximately 0.050 mm before conducting the test. The top and bottom surfaces of the specimen were wiped clean, and the axis of the specimen was placed in the testing area to align with the center of the bearing block. A load of 0.25 ± 0.05 kN/sec was applied at a constant rate. As the sample initiated to fail, the ultimate load at which the sample failed was noted.

Figure 3-19 Compressive strength test setup

3.5.2 Shear Strength Test

To evaluate the shear strength of concrete mixtures, two specimens measuring 150 mm x 150 mm x 450 mm with two notches on the opposite sides were prepared. The specimens for the test were produced by using a mold that was assembled at the University of Waterloo as illustrated in Figure 3-20 (Omidi 2021). A shear test was performed on specimens 28 days after curing. The shear load is applied constantly at a rate of 0.25 ± 0.05 kN/sec by the universal testing machine as shown in Figure 3-20. The specimen was designed in such a manner that the shear failure occurred at a known plane. The above-mentioned method is known as the single shear test as the failure occurs only at a single plane (Omidi 2021).

The shear strength of the concrete is determined by the formula given in equation 3.1

$$\tau_s = \frac{P_s}{bh} \qquad \textit{Equation 3.1}$$

Where

τ_s = shear strength of the sample in MPa

P_s = maximum shear load in kN

b = width of the sample in mm

h = height of *shear* failure plane in mm

Figure 3-20 Shear strength test setup

3.5.3 Splitting Tensile Strength Testing

Splitting tensile tests were performed under CSA A23.2-13C (CSA, 2009) using 100 x 200 mm concrete cylinders. The specimens were tested after 28 days of curing. All the results were recorded and presented as a three-test-sample average. Specimens were placed under the bearing block, as shown in Figure 3-21. The specimen was placed in the testing area to align with the center of the bearing block. A continuous load of 0.7 to 1.4 MPa/min was applied to each specimen. The applied load was measured using the testing equipment that logged the ultimate load when the sample started to fail. This maximum load in kN was logged, and the following equation 3.2 was used to determine the value of splitting tensile strength.

$$T = \frac{2 \cdot P}{\pi \cdot l \cdot d}$$ *Equation -3.2*

Where:

T = splitting tensile strength in MPa

P = maximum applied load indicated by the testing machine

l = length of specimen in mm

d = diameter of specimen in mm

Figure 3-21 Splitting tensile strength setup

3.5.4 Water Absorption Test

The water absorption test was carried out by CSA A23.2-11C. Cylinders with dimensions 100 x 200 mm were used for the test after 28 days of curing. Each specimen was placed in containers of size 200 x 300 mm. The oven-dried mass of each specimen was obtained by placing them in an oven at a temperature of 100 to 110℃ for 24 hours. Later, the saturated mass of samples was determined by immersing them in water at approximately 21˚C for 48 hours. The samples were kept immersed until two successive measurements of the mass of the surface-dried samples at intervals of 24 hours indicated constant mass. The capability of water absorption was calculated as indicated in equation 3.4.

$$Absorption\ after\ immersion, \% = \left[\frac{B-A}{A}\right] * 100 \qquad \textit{Equation 3.4}$$

Where

A = mass of oven-dried sample in g

B = mass of surface- dry sample in the air after immersion in g

3.5.5 Freeze-Thaw Durability Test

The de-icing salts freeze-thaw durability test is used to determine the resistance of the surface of the concrete to repeated cycles of freezing and thawing. The freeze-thaw durability test was carried out following CSA A.231.2-7.3. The test specimens used were 100 x 200 mm cylinders, the specimens were brushed clean with a brush, and all loose burrs and edges were removed. The samples were placed in containers of size 200 x 300 mm and immersed in a solution with 3 ± 0.1% of sodium chloride for 24 hours at a minimum temperature of 15 °C before the freeze-thaw test.

The specimens were subjected to a continuous freeze-thaw cycle, one freeze-thaw cycle was completed every 24 h and each cycle consisted of 16 ± 1 hour of cooling followed by 8 ± 1 hour of heating. The specimens were exposed to a minimum temperature of -18 °C for 16 ± 1 hour and room temperature for 8 ± 1 hour. The loss of mass for each sample was measured at 7, 28, and 49 cycles respectively. After 28 cycles of freezing and thawing, if the average loss of mass for at least three specimens of each mixture was found to be greater than 225 g/m^2, the specimens were subjected to 49 cycles of freeze and thaw. After 7 and 28 cycles, the specimens were washed with distilled water to remove all loose particles. The particles and the spalled material were then collected and filtered using an 80 μm sieve and dried to a constant mass in the drying oven for 24 ± 1 h. This residue is considered the mass loss and is expressed in grams.

Figure 3-22 Samples after undergoing 16 hours of freezing

3.6 Summary

This chapter discussed the research methodology used in this study. The properties of materials used for this study was discussed. The test procedures for determining some important properties of aggregates were introduced. The test procedures for fresh concrete tests like slump and air content was explained. The test procedure for hardened concrete tests like compressive strength, shear strength, splitting tensile strength, water absorption and freeze-thaw were also explained.

Chapter 4
Results and discussion

4.1 Aggregate Properties

4.1.1 Specific Gravity and Absorption

The specific gravity and absorption results for NA and CRCA are shown in Table 4-1. There is not much of a difference between the specific gravities of NA and CRCA which is 2.7 and 2.64 respectively. This value indicates the CRCA's quality and validates its use in concrete. As depicted in Table 4-1, the values of absorption for NA and CRCA vary significantly. The presence of adhered mortar accounts for the higher absorption value in CRCA and makes it more susceptible to water absorption due to the higher porosity of adhered mortar (Al-Bayati, 2019). It has been established that adhered mortar in RCA increases water absorption and decreases density (Wong, Sun, and Lai 2007). The water absorption value normally ranges from 0.2% to 0.8%, for CRCA the water absorption value is 5.91% which is significantly high when compared to the normal range (Al-Bayati, 2019). These findings support the findings of previous studies, which indicate that RCA’s significantly higher absorption capacity than NA (Butler, West, and Tighe 2013).

4.1.2 Abrasion Resistance

Abrasion resistance testing for various aggregate types accounts for the durability and strength of aggregate under wet conditions (Al-Bayati, 2019) . This test determines the hardness of aggregate and its abrasion resistance. In general, a lower abrasion loss percentage indicates that less adhered mortar is lost. The obtained results, as indicated in Table 4-1, show that there is a substantial difference in values of abrasion loss for NA and CRCA. CRCA has an abrasion loss of 23.57 %, which is significantly higher than NA's loss of 12.58 %. According to various literature, most RCAs have an abrasion loss value of roughly 35 to 45 % (Al-Bayati, 2019). As expected, NA has a higher value for toughness and higher deterioration resistance, however, when compared to abrasion values described in the literature, the CRCA used in this study has lower abrasion loss values, indicating strong types of CRCA.

4.1.3 Adhered Mortar Loss

In terms of RCA, adhered mortar loss is an important factor to consider. Adhered mortar loss represents the amount of adhered mortar that can be removed from the RCA using various mechanical and chemical methods (Al-Bayati, 2019). A mechanical method using a Micro-Deval apparatus was employed to determine the loss of adhered mortar in CRCA. The percentage loss for the CRCA was 3.02%. The results show that the CRCA has a high resistance to degradation and is suitable for use in concrete.

Table 4-1 Properties of natural and recycled coarse aggregate

Aggregate Properties	NA	CRCA
Apparent Specific Gravity	2.70	2.64
Absorption (%)	0.66	5.91
Micro-Deval Abrasion Loss (%)	12.58	23.57
Adhered Mortar (%)	-	3.02

All of the aggregate properties investigated in this study meet the criteria for use in concrete. The values of abrasion loss and adhered mortar loss of the CRCA indicate that it is a strong type of aggregate.

4.1.4 Concrete Naming Convention

As seen from the literature review in section 2.4.6.4 of chapter 2, three variants of selected mixtures with CRCA replacement and five additional mixtures were chosen based on practical considerations and the availability of sustainable materials.

Table 4-2 Mixture summary and Designation

Sl No.	CRCA Content (%)	GGBFS content (%)	GP Content (%)	Mix-Designation
1	0	0	0	CM
2	20	0	0	RC 20
3	20	20	0	RC 20/S 20
4	40	20	10	RC 40/S 20/ G 10

In total, eight mixtures were selected for laboratory testing, along with a Control Mix. However, due to the unprecedented situation caused by the Covid-19 pandemic, which impacted material supply, there was only enough material to cast three mixes and the control mix. As a result, Mix 1, Mix 6, and

Mix 8 as shown in Table 2-3 were chosen, along with the control mix, to be tested in the laboratory for this study.

The CRCA and SCM replacement levels were used to differentiate the sample sets. To keep track of these variables, a standard naming pattern was implemented for various concrete mixtures.

Each concrete type was named based on three distinct components. The mixtures are labeled as RCx/Sy/Gz, where RC stands for CRCA and "x" represents the percentage replacement. The letter S denotes the presence of GGBFS in the concrete mixture, and the letter "y" denotes the percentage of cement replaced by GGBFS. G denotes GP in concrete mixtures, and "z" denotes the percentage of cement replaced with GP (For eg. RC20/S20/G10 represents a concrete mixture with 20% CRCA, 20% GGBFS, and 10% GP). The control mixture however is denoted as “CM” since it does not contain CRCA or SCM. The mixture designation is indicated in Table 4-2.

4.2 Test Results

4.2.1 Slump

A slump test was performed on each batch of concrete mix to analyze and evaluate its workability Figure 4-1 depicts the slump and water-cement (w/c) ratios used in each mixture. The slump value of 55 ± 5 mm was maintained across all the mixtures. These slump values indicate that the mixtures are medium workable and are commonly used for regular reinforced concrete placed with vibration. However, the w/c ratio for each mixture varied to achieve the slump value of 55 ± 5 mm. The w/c ratios of all the mixes including CM were less than 0.5. The highest value of the w/c ratio is observed in RC 20 mix. The presence of higher percentages of CRCA in this mixture compared to the other mixtures explains the higher w/c ratio values.

Many of the characteristics of CRCA can be seen to be dependent on the residual mortar that is attached to the aggregates because, with the increase in the mortar content, the CRCA tends to have increased porosity and thus lowered resistance to abrasion. The combined effect caused by the presence of fine particles due to abrasion and increased absorption from residual mortar affects the water demand of the concrete mix, which seems to negatively impact the fresh properties of RCA concrete. However, the negative impacts, in this case, were minimized due to the pre-conditioning of aggregates by thoroughly washing them to remove as much of the adhered motor layer as possible.

Despite the presence of CRCA in the mixes, the w/c ratio of RC 20/S 20 and RC 40/S 20/G 10 is lower or equal to that of CM. The lowered demand for water in these mixes can be attributed to the presence of SCM. Smooth and dense SCM particles absorb less water than portland cement particles, making SCM-containing concrete more workable than concrete with only cement (Cahyani and Rusdianto 2021).

The slump test results agree with previous research works, indicating that more water is required in concrete containing CRCA to achieve similar workability as concrete containing NA and that the inclusion of SCM in concrete mixture reduces the water demand and makes the concrete more workable (Cahyani and Rusdianto 2021; Yehia et al. 2015).

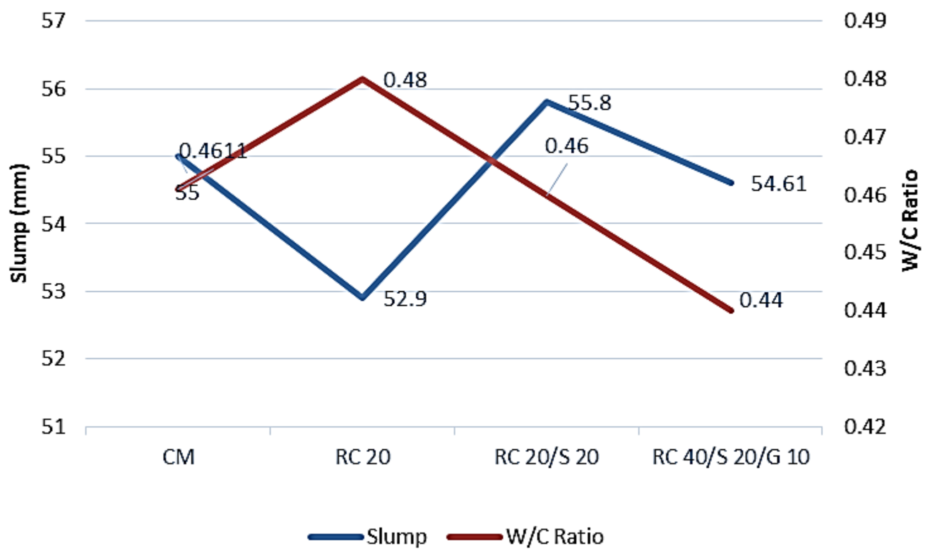


Figure 4-1 Slump and water-cement ratio values for all mixtures

4.2.2 Air Content

According to the CSA A23.1 specification, the air content testing was performed by using the pressure method. The obtained findings indicate that all the mixtures met the 5-8% air content specifications, as shown in Table 4-3. The results indicate that all the mixtures had comparable air void content to that of the CM. To ensure all mixtures adhered to the standards, air content was measured immediately following the mixing procedure. To achieve the specified standards, an air-entraining agent (AEA) was used in all the mixtures.

Concrete contains a volume of air bubbles which are usually formed during the mixing of concrete. In the absence of an AEA or a contaminant that entrains air, the total volume of air entrapped in concrete is usually between 1% and 3%. Therefore, an AEA must be introduced into the concrete to enhance the amount of air present in the concrete (Gagné 2016). The entrained air radically improves the durability of concrete exposed to moisture during freeze-thaw cycles and improves the concrete's resistance to surface scaling caused by chemical de-icers. AEA also reduces the surface tension of a fresh cement composition at low concentrations, increases the workability of fresh concrete, and reduces segregation and bleeding (Niaounakis 2006).

Table 4-3 Air void content values of mixtures

Mixtures	Air Void Content (%)
CM	5.1
RC 20	5.2
RC 20/S 20	5
RC 40/ S 20/G 10	5.3

4.2.3 Compressive Strength

Compressive strength was tested as highlighted in section 3.5.1. The samples were cured in water at a temperature of 23 °C. The first compressive strength values were measured after 1 day of curing and then subsequently at 7 and 28 days. Figure 4-2 shows the compressive strength of all the mixtures, and Figure 4-4 illustrates the development of compressive strength for all the mixtures, respectively.

It can be seen that the 28 days strength ranges from 38.5 MPa to 40.5 MPa. Mix RC 40/S 20/G10 exhibits a strength of 40.5 MPa and performs at par with the CM which has 40 MPa compressive strength at 28 days. Mix RC 20/S 20 also demonstrates a comparable strength of 39.9 MPa and RC 20 shows the lowest strength. The 20% replacement level of CRCA reduces the compressive strength of the RC 20 mix compared with CM at 7 and 28 days. However, this adverse impact was made up by replacing 20% cement with SCM (GGBFS) at 28 days as seen in mix RC 20/S 20. Mix RC 40/S 20/G 10 has the highest compressive strength at 28 days even with a 40% replacement level of CRCA and 30% SCM, which indicates that pozzolanic materials can contribute to the increase in strength and reduces the weakness that is caused by a high percentage of CRCA replacement level. The findings are extremely encouraging in terms of increasing the use of CRCA and SCM applications in concrete pavements to reduce natural aggregate consumption and CO_2 emissions.

Figure 4-5 shows strength gain curves for all the mixtures plotted along with the strength gain curve for CM. It is observed that the strength curve is observed to be prominent at early ages in mixtures without pozzolanic materials, and it tends to stabilize earlier. The curve of the mixtures with pozzolanic materials, on the other hand, is less prominent in earlier ages but tends to develop in the later stages.

A research was conducted as part of this project that used finite element modeling to replicate field conditions to assess the effectiveness of uniquely shaped ICPs carrying heavy loads. As a result, it was found that the allowable range of stress for individual paver was 3.41 MPa (Omidi 2021). The compressive strength values for all the mixtures range between 38.5 to 40.5 MPa and fall within the permissible range of stress.

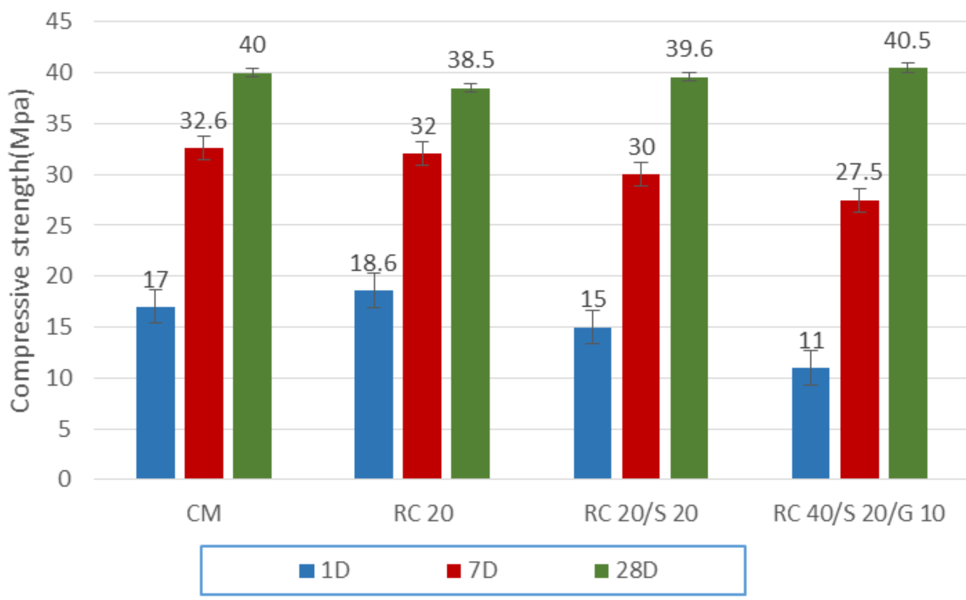


Figure 4-2 Compressive strength at 7, 14, and 28 days for all mixtures

Although the strength of RC 20/S 20 and RC 40/S 20/G 10 mixtures increased slowly, their compressive strength is comparable to CM, indicating their applicability in ICPs in terms of compressive strength.

The obtained results are consistent with other research findings, indicating that the incorporation of RCA, in general, affects compressive strength. The percentage replacement of RCA has a greater impact on compressive strength values (Soldado et al. 2021; Tiwari and Nateriya 2016). However, the compressive strength of concrete with RCA can be improved by substituting it with varying percentages of SCMs (Ann et al. 2008; Çakir 2014; Soldado et al. 2021).

Figure 4-3 Samples after undergoing compression test

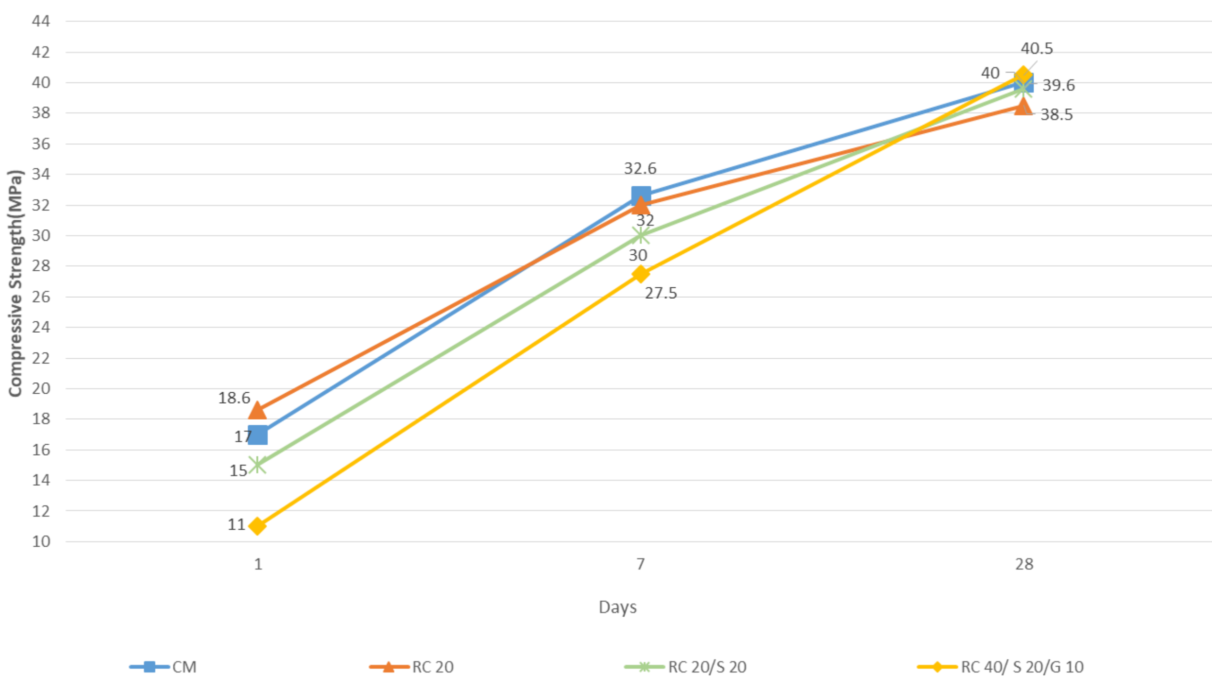
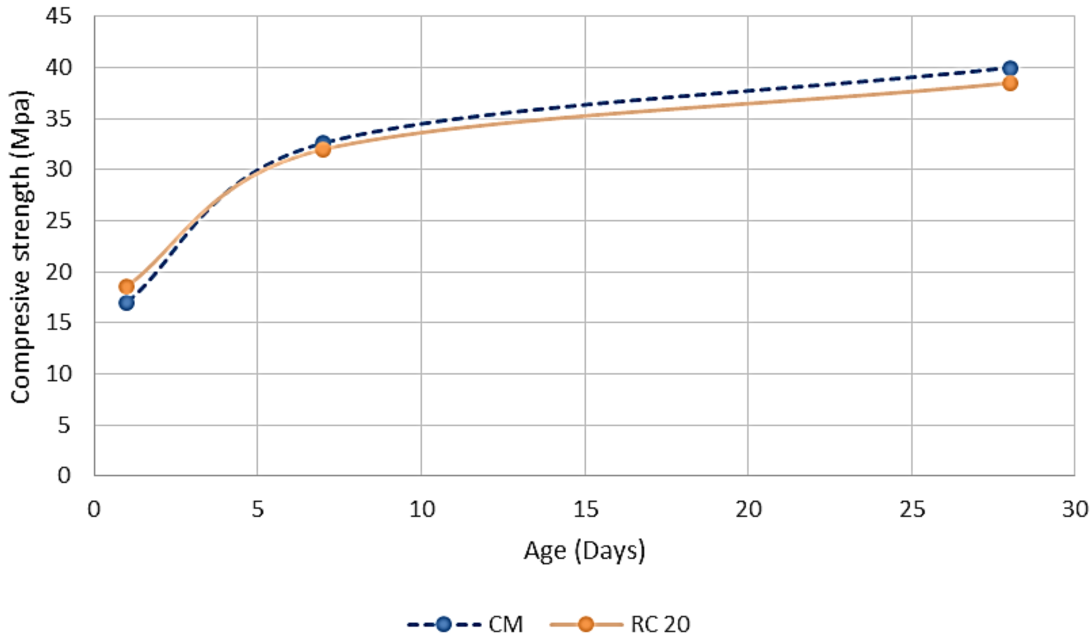
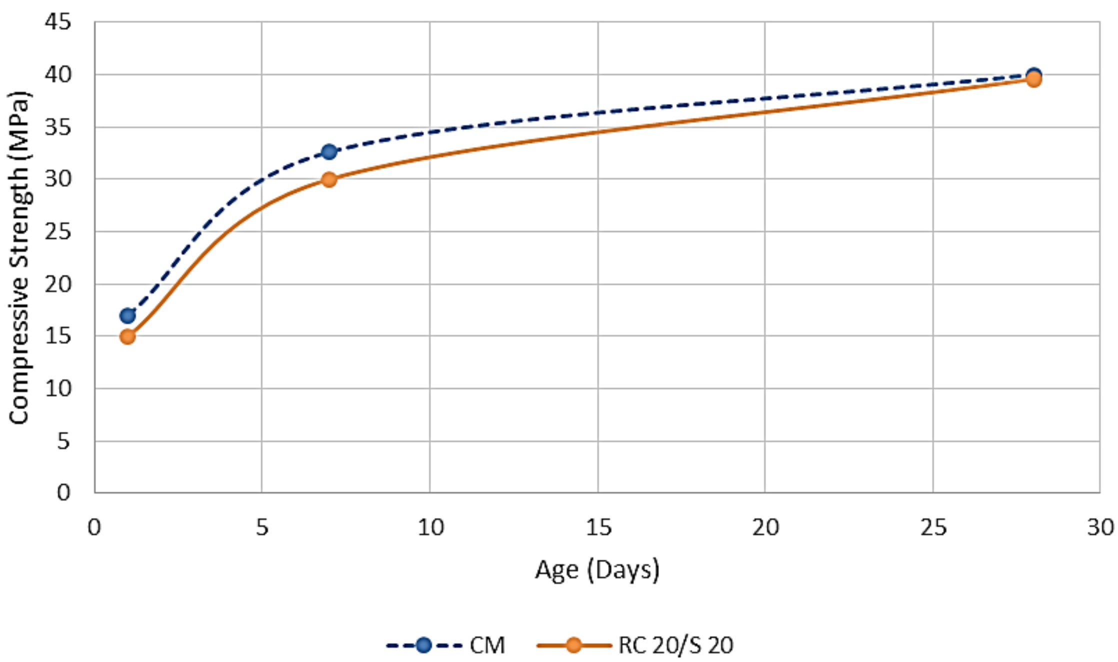


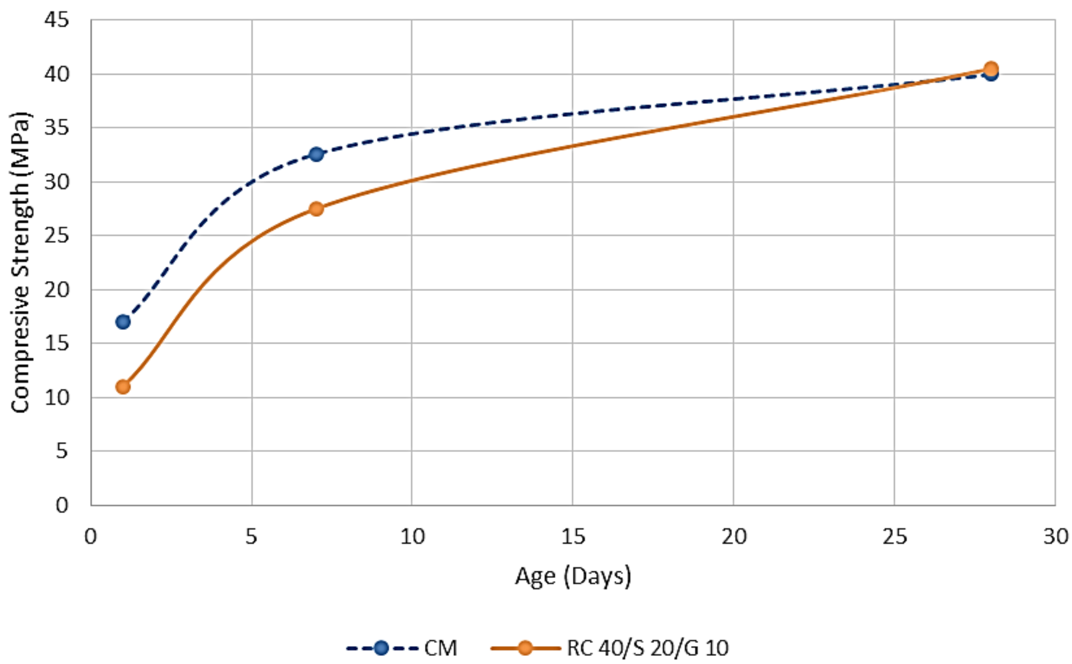
Figure 4-4 Compressive strength development for all the mixtures



a. Strength gain curve for Mix RC 20 plotted against the strength gain curve for CM



b. Strength gain curve for Mix RC 20/S 20 plotted against the strength gain curve for CM



c. Strength gain curve for Mix RC 40/S 20/G 10 plotted against the strength gain curve for CM

Figure 4-5 (a,b,c) Strength gain curves for all the mixtures plotted along with the strength gain curve for the control mix.

4.2.4 Shear Strength

The shear strength test was carried out as mentioned in the previous section. The results of maximum shear load (Ps) and shear strength (τs) for all the mixtures have been shown in Table 4-4 and have been graphically plotted in Figure 4-6. The shear strength results have been correlated with the percentage replacement of NA with CRCA and cement with SCMs.

It can be observed that CM, which has 0% of CRCA and SCM gives the highest value for shear strength. As the percentage of CRCA increases to 20, the decrease in the shear strength is negligible since it is less than 1% in RC 20 mix. Mix RC 20/S 20 performs closest to the shear strength of CM. However, the mix RC 40/S 20/G 10 has the lowest value for shear strength with a decrease in value by around 20.27%.

It can be seen that the percentage replacement of CRCA considerably affects the shear strength properties of concrete. However, it is also observed that the addition of SCM does not increase the shear strength drastically. This slight increase is demonstrated by the mix RC 20/S 20, which has 20 %

SCM as opposed to 0% SCM in RC 20 mix, and the shear strength value for RC 20/S 20 is just around 1% more than that of RC 20.

According to the findings from the finite element modeling, the maximum shear stresses induced in ICPs simulated to carry heavy load was 1.42 MPa (Omidi 2021). If the maximum stress induced due to shear exceeds the shear strength of the ICP, the pavement fails. Since the values of shear strength for all the mixtures range between 4.5 to 5.7 MPa, they would provide adequate shear strength.

The shear strength value of Mix RC 20/S 20 is closest to that of CM. The results are extremely encouraging in terms of expanding the use of CRCA and SCM applications in concrete pavements to reduce NA consumption and CO_2 emissions.

Table 4-4 Shear strength results

Concrete Mixtures	Maximum Shear Load (PS) kN	Shear Strength (τs) MPa	Percentage Decrease in Shear Strength over Control Mix
CM	128.8	5.72	NA
RC 20	127.7	5.67	Less than 1%
RC 20/S 20	128.5	5.71	Less than 1%
RC 40/S 20/G10	102.7	4.56	20.27%

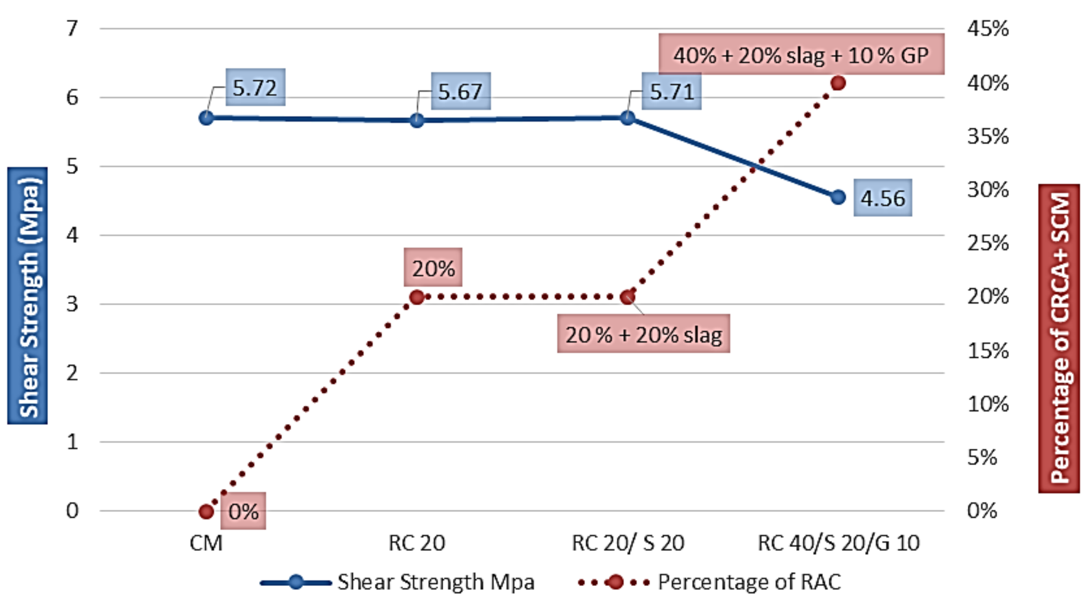


Figure 4-6 Shear strength results along with the percentage of RCA and SCMs replaced for all mixes

Despite extensive research into RCA's shear behavior, the effects of RCA on the shearing strength of concrete are not fully understood (Rahal 2017). Based on a review of the literature, the results obtained in this study fully agree with other research works and indicate that the incorporation of RCA reduces the shear strength of concrete (Rahal 2017) and the incorporation of SCMs has no significant effect on the shear strength of concrete.

Figure 4-7 Specimen after undergoing shear test

4.2.5 Splitting Tensile Strength

The splitting tensile strength for all specimens was carried out after 28 days, as mentioned in section 3.5.3. The results of maximum applied load (P) and splitting tensile strength (T) for all the mixtures have been shown in Table 4-5 and Figure 4-8.

The results of splitting tensile strength have been correlated with the percentage replacement of NA with CRCA and cement with SCM. It can be observed that CM has the highest value for tensile strength. As the percentage of CRCA increases to 20% in the RC 20 mix, the decrease in the tensile strength is negligible as it is around 1 %. Whereas, when compared to the CM, mix RC 20/S 20 has a 2.5 % reduction in tensile strength. However, the RC 40/S 20/G10 mix has the lowest tensile strength value, with a decrease of around 14.5%.

Generally, it is observed that there is a decrease in splitting tensile strength as the replacement of RCA increases. This decrease can be attributed to the higher porosity, lower density, and lower overall strength of RCA. Furthermore, the decrease in splitting tensile strength of mixtures with RCA can be attributed to the volume and strength of the original adhered mortar surrounding aggregates. Based on the results, a similar observation to that of shear strength values can be made, indicating that the addition of SCM has no significant contribution to improving the splitting tensile strength of the concrete.

Table 4-5 Tensile strength results

Concrete Mixtures	Maximum Shear Load (Ps) KN	Tensile Strength (T) Mpa	Percentage Decrease in Tensile Strength over Control mix
CM	149.8	4.77	NA
RC 20	148.3	4.72	1.00%
RC 20/S 20	146	4.65	2.50%
RC 40/S 20/G 10	128	4.08	14.50%

The splitting tensile strength results are consistent with other studies that show that the splitting tensile strength of RCA concrete is lower than the splitting tensile strength of NA concrete (Çakir 2014; Maruyama 2014; Mcneil and Kang 2013; Padmini, Ramamurthy, and Mathews 2009). In addition, it has been observed that the use of SCM is less effective in increasing the tensile strength of the specimen (Ann et al. 2008).

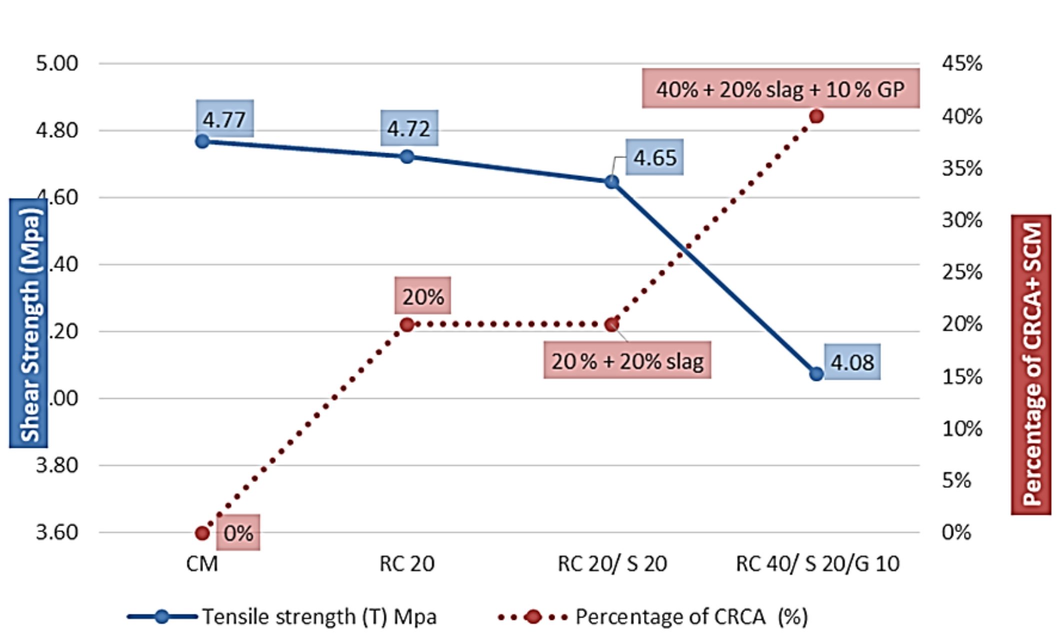


Figure 4-8 Splitting tensile strength results along with various percentages of RCA and SCM's replaced for all mixtures

The tensile strength values in this study show that when the CRCA replacement level is low (20% in this case), the tensile strength is less affected, with the value decreasing by only about 1% in mix RC 20 compared to CM. This finding is encouraging for the use of CRCA in concrete.

Figure 4-9 Specimens after undergoing split tensile strength test

4.2.6 Water Absorption

The water absorption (WA) test was carried out after 28 days, as mentioned in section 3.5.4. The results of the absorption for all the mixtures are taken as the average of three samples and shown in Figure 4-10.

It can be observed from the results that the highest water absorption value is registered for the RC 20 mix, which is around 13% higher than that of the CM. While, interestingly, in mixes RC 20/S 20 and RC 40/ S 20/ G 10, the absorption values are about 7% lower than the CM.

In general, the results show that the addition of SCM improves WA resistance significantly. The formation of additional CS-H bonds as a result of the addition of SCM, which also reduces the size and connectivity of pores, can be attributed to the improvement in WA resistance. In addition to the pozzolanic reaction, the filler effect of SCM reduces pore size, disrupting the connections between pores (Qureshi, Ali, and Ali 2020).

According to CSA A23.2, the average absorption of all specimens shall be less than 5%, and the absorption of individual paver shall be less than 7% (CSA A231.1/A231.2 2006). The average values of absorption for all the mixtures range from 3.77 % to 4.07 % and are well under the specified values. Therefore, all the mixtures show adequate resistance to absorption.

The obtained results agree with the work of several researchers, who show that as the RCA content increases, so do the absorption values, which are generally attributed to RCA's high absorption capacity (Bao et al. 2020; Kwan et al. 2012; Soldado et al. 2021). The incorporation of SCM has been observed to reduce WA values, owing to its pore-filling effect (Qureshi, Ali, and Ali 2020; Soldado et al. 2021).

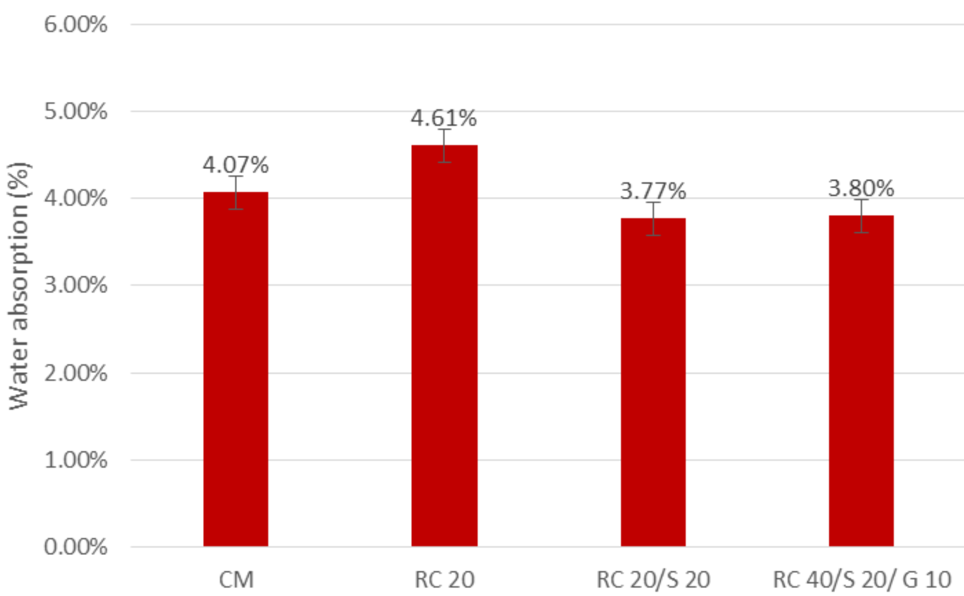


Figure 4-10 Water absorption test results of all mixtures

4.2.7 Freeze-Thaw Durability

The results of the freeze-thaw test for specimens of all the mixtures are presented in Table 4-6. The freeze-thaw test was performed as mentioned in section 3.5.5. The testing consisted of 28 freeze-thaw cycles. Three samples for each mixture were tested, and the results represent the average loss of mass of all three samples at 7 days and 28 days respectively.

Table 4-6 Loss of mass after freeze-thaw treatment at 7 and 28 days

Concrete Mixtures	Loss of Mass (g) in 7 Days	Loss of Mass (g) in 28 Days	Total Loss of Mass
CM	55.33	111.26	166.26
RC 20	92.93	121.00	214.00
RC 20/S 20	15.00	55.40	70.40
RC 40/S 20/G 10	10.00	27.95	37.95

It is observed that mix RC 20 had the highest loss of mass both at 7 days and 28 days, which can be explained due to the presence of 20% CRCA in the mixture. Failure mechanisms in cementitious systems subjected to freeze-thaw cycles are based on hydrostatic pressure and osmotic pressure (H. Liu et al. 2020). Some studies showed that the strength of old mortar attached to the RCA is lower than that of NA. Hence, its resistance to hydraulic and osmotic pressures caused by the freeze-thaw cycles is lower which results in a higher loss of mass (Hao et al. 2018).

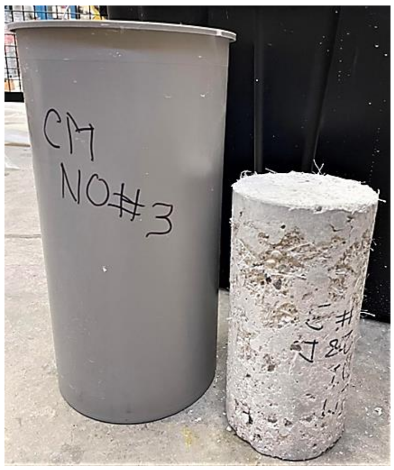
On the other hand, mixes RC 20/S 20 and RC 40/S 20/G 10 have a lower loss of mass compared to CM. As mentioned earlier, hydrostatic pressure and osmotic pressure play an important role in resistance to the freeze-thaw cycles (H. Liu et al. 2020). The hydrostatic pressure in specimens is closely related to the pore structure. The wear of cement-based materials, which changes the microstructure under freeze-thaw cycles, is also related to the specimen pore structure (Hao et al. 2018). The filler effect of SCM in addition to the pozzolanic reaction seems to reduce the pore size, thereby improving the pore structure as a whole in RC 20/S 20 and RC 40/S 20/G10 mixes (Qureshi, Ali, and Ali 2020).

Table 4-7 Percentage of a total loss of mass after freeze-thaw treatment

Concrete Mixtures	Average Original Dry Mass (g)	Average Total Loss of Mass (g)	Average Mass Loss (%)
CM	3823.62	166.26	4.34 %
RC 20	3672.83	214.00	5.83%
RC 20/S 20	3843.00	70.40	1.83%
RC 40/S 20/G 10	3762.85	37.95	1.00%

According to CSA average loss of mass of concrete pavers exposed to freeze-thaw cycles that are immersed in 3%, NaCl solution should be less or equal to 1%. As shown in Table 4-7 only the RC 40/S 20/G 10 mix satisfies this condition and seems to provide adequate resistance to freeze-thaw. Although only mix RC 40/S 20/G 10 provides adequate freeze-thaw resistance in Canadian climates or similar climates where temperatures fluctuate a lot, other mixes such as RC 20/S 20 can be used in warmer areas where temperatures do not fluctuate as much, providing adequate resistance strength and encouraging the use of CRCA and SCMs for ICP production in such climatic areas.

The freeze-thaw durability test results are consistent with other studies that conclude that impurities in RCA reduce concrete's resistance to an aggressive environment. The lower freeze-thaw resistance of RCA is also due to its higher water absorption capacity; thus, like the RCA replacement and water-cement ratio increases, the freeze-thaw resistance of concrete decreases (Ann et al. 2008; Kou, Poon, and Etxeberria 2014; Xiao 2018). However, combining SCMs and AEA improves the freeze-thaw durability of concrete, which is usually attributed to improved pore structure and an efficient air void system (Hao et al. 2018; Jain et al. 2012; H. Liu et al. 2020).



a. CM after 28 freeze-thaw cycles

b. RC 20 mix after 28 freeze-thaw cycles

c. RC 20/S 20 mix after 28 freeze-thaw cycles

d. RC 40/S 20/G 10 mix after 28 freeze-thaw cycles

Figure 4-11 (a,b,c &d) Specimens after 28 freeze-thaw cycles

4.3 Discussion

One of the main goals of this research was to assess the feasibility of using CRCA and SCM as partial replacements for NA and cement in concrete for the production of ICP.Concrete mixtures with varying

CRCA and SCM replacement percentages performed similarly to CM across all testing categories. Concrete mixtures containing up to 40% CRCA and 30% SCM replacement levels showed promising results and performed equally well as the CM.

A Single-factor ANOVA test was performed to confirm and identify if there is any significant difference between the averages of the results gathered from various tests. The measured parameters of concrete such as compressive strength, shear strength, tensile strength, absorption, and freeze-thaw durability were characterized as dependent factors, whereas the percentage of CRCA and SCM used in the concrete mixtures were identified as independent factors. The significance level was set at 0.05 to quantify the statistical significance of the outcome and the p-value lower than 0.05 to characterize a variable as significant.

The following Table 4-8 shows the summary of the obtained results of all the mixtures:

Table 4-8 Summary of results

Mix	Slump		Air Void Content (%)	Compressive strength(MPa)			Shear Strength (MPa)	Splitting tensile strength (MPa)	Water Absorption (%)	Freeze-thaw durability	
	Slump (mm)	w/c ratio		1 D	7 D	28 D				Loss of mass 7 cycles (g)	Loss of mass 28 cycles (g)
CM	55	0.461	5.1	17	32.6	40	5.72	4.77	4.07	55.33	111.26
RC 20	52.9	0.48	5.2	18.6	32	38.5	5.67	4.72	4.61	92.93	121
RC 20/S 20	55.8	0.46	5	15	30	39.6	5.71	4.65	3.77	15	55.4
RC 40/S 20/G 10	54.61	0.44	5.3	11	27.5	40.5	4.56	4.08	3.8	10	27.95

Table 4-9 summarizes the results obtained from one way ANOVA test. The test was conducted to identify the statistical significance of CRCA in the concrete mixtures by comparing the test results of the CM and RC 20 mix. To identify the statistical significance of GGBFS as SCM in the concrete mix a comparison in the results of RC 20 and RC 20/S 20 mixes were made. It is observed that the compressive strength of RC 20/S 20 mixes after 1 and 28 days is statistically significant because the p-value is less than 0.05, and the value of F actual is greater than F critical.

Table 4-9 Results obtained from one way ANOVA test

Compressive strength		P-value	F actual	F critical	Significance
1 Day	20% CRCA	0.06	6.25	7.7	Insignificant
	20% CRCA with 20% GGBFS	0.002	26.72	5.1	Significant
7 Days	20% CRCA	0.64	0.25	7.7	Insignificant
	20% CRCA with 20% GGBFS	0.18	2.27	5.98	Insignificant
28 Days	20% CRCA	0.24	1.92	7.7	Insignificant
	20% CRCA with 20% GGBFS	0.047	8	7.7	Significant
Shear Strength					
20% CRCA		0.36	1.35	18.51	Insignificant
20% CRCA with 20% GGBFS		0.57	0.46	18.51	Insignificant
Tensile Strength					
20% CRCA		0.17	2.65	7.7	Insignificant
20% CRCA with 20% GGBFS		0.31	1.29	7.7	Insignificant
Absorption					
20% CRCA		0.11	4.16	7.7	Insignificant
20% CRCA with 20% GGBFS		0.53	0.46	7.7	Insignificant
Freeze-Thaw Durability					
Loss of mass in 7 Days	20% CRCA	0.0001	231.17	7.7	Significant
	20% CRCA with 20% GGBFS	0.000004	1137.85	7.7	Significant
Loss of mass in 28 Days	20% CRCA	0.64	0.24	7.7	Significant
	20% CRCA with 20% GGBFS	0.009	22.18	7.7	Significant

However, the compressive strength after 7 days for the same mix appears statistically insignificant. This explains the pozzolanic activity in RC 20/S 20 mixes as a result of the presence of GGBFS, which causes the strength gain to occur later. The effects of 20% CRCA and 20% SCM on shear strength, tensile strength, and absorption in concrete mixtures appear to be statistically insignificant. For both RC 20 and RC 20/ S 20 mixes, the mass loss due to the freeze-thaw durability test is statistically significant.

It is reasonable to conclude that the differences in the results are statistically significant, indicating that incorporating SCM along with CRCA significantly affects the 1 day and 28 days compressive strength of concrete. Adding 20% CRCA and 20% SCM appears to affect concrete's freeze-thaw durability substantially. The full ANOVA analysis can be found in Appendix A.

The experimental results, combined with the statistical analysis, provide compelling evidence to encourage the use of CRCA and SCM in concrete mixtures, not only in ICP but also in structural concrete, as the values of obtained mechanical properties are promising.

4.4 Summary

This chapter illustrates the results obtained from the laboratory tests. The effects of varying percentages of CRCA and SCMs on fresh and hardened properties of concrete mixtures were evaluated. The results of mixtures with recycled materials were also compared with the control mix. A single factor ANOVA test was also carried out to determine the statistical significance of CRCA 90 and SCMs in the concrete mixtures. Based on the findings, the following conclusions were reached, as shown in the following chapter.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The main aim of this study was to assess the mechanical and durability performance of ICPs containing CRCA and SCMs for their performance in typical high-traffic urban areas. Three concrete mixtures containing various percentages of CRCA and SCMs as partial replacements of NA and cement and GUL cement instead of conventional cement along with a CM were studied to achieve this goal. The mixtures were selected based on the Life Cycle Impact Assessment and laboratory tests were conducted. The conclusions drawn from these studies are summarized below.

5.1.1 Fresh Concrete Test

- Concrete mixtures containing CRCA and SCMs yielded workable mixtures. The slump value for all of the mixtures was found to be 55 ± 5 mm. To achieve the slump value of 55 ± 5 mm, the w/c ratio for each mixture was varied. The w/c ratio of mixtures containing CRCA was greater than the CM.
- The air void content in all mixtures ranged from 5-5.3 %. All of the mixtures met the 5-8 % air content requirements. The presence of AEA in all of the mixtures accounts for the comparable air content.

5.1.2 Hardened Concrete Test

- The compressive strength ranged from 38.5 MPa to 40.5 MPa after 28 days. RC 40/S 20/G 10 mixes had the best compressive strength value. Mixtures containing CRCA and SCMs had comparable strength values and performed similarly to the CM. The mixture without SCMs and only CRCA, on the other hand, had a lower strength value. This decrease indicates that the addition of CRCA alone has a negative effect on the compressive strength of concrete. As a result, in terms of compressive strength, the addition of CRCA with SCMs ranging from 20-40% and 20-30%, respectively, as partial replacement of NA and cement can produce sustainable concrete mixtures for use in ICPs.
- Previous research conducted as part of this project, stimulated field conditions to assess the performance of ICPs catering to heavy loads, using finite element modeling and found that the

allowable range of stress was 3.41 MPa (Omidi 2021). All the mixtures have compressive strengths ranging from 38.5 to 40.5 MPa, which are well within the permissible stress range.

- The shear strength value for CM was the highest when compared to other mixes. The shear strength value decreased by up to 20.27 % as the percentage replacement of CRCA in mixtures increased. The results showed that the addition of SCMs had no significant effect on the shear strength of the concrete. However, a negligible difference of less than 1% in the shear strength value was seen when the replacement percentage of CRCA was 20%. Therefore, the results encourage using CRCA up to at least 20% as a replacement for NA in ICPs to reduce natural aggregate consumption.

- According to the findings from the finite element modeling, the maximum shear stress in ICPs subjected to heavy loads is 1.42 MPa (Omidi 2021). Although all the mixtures meet the required shear strength value, RC 20/S 20 mixes had the closest value to that of CM.
- CM had the highest splitting tensile strength value. The value for splitting tensile strength decreased up to 14.5 % as the percentage of CRCA replacement increased to 40 %. The RC 40/S 20/G 10 mixes had the lowest value. However, when the CRCA replacement percentage was 20%, there was a negligible difference in tensile strength of less than 1%. The results also show that the addition of SCMs had no significant effect on the splitting tensile strength of the concrete. Therefore, the findings encourage the use of CRCA up to 20% as a partial replacement for NA in ICPs to reduce natural aggregate consumption.
- The results for the water absorption show that the RC 20 mix had the highest value, which was 13% higher than the CM. The values for absorption for all the mixtures ranged from 3.77 % to 4.07 %, which is well under the specified values. Whereas, the values for RC 20/S20 and RC 40/S20/G 10 were around 7% lower than the CM and indicate that water absorption resistance improves significantly with the addition of SCMs.
- Loss of mass after the freeze-thaw test was highest for RC 20 mix and can be attributed to the presence of just CRCA in the mix. RC 20/S 20 and RC 40/S 20/G10 mixes had a lower loss of mass when compared to the CM and can be attributed to the presence of SCMs along with CRCA in the mixtures. According to CSA average weight loss of pavers after the freeze-thaw cycle must be less than or equal to 1%, and only RC 40/S 20/G 10 meets this requirement.

- Only mix RC 40/S 20/G 10 provides adequate freeze-thaw resistance in Canadian or similar climates with frequent temperature fluctuations. However, other mixes such as RC 20/S 20 can be used in warmer climates with less frequent temperature fluctuations, providing adequate resistance strength and still encouraging the use of CRCA and SCMs for ICP production.
- A single factor ANOVA test was used to determine whether there is a significant difference between the averages of the results gathered from various tests. According to the findings of this study, incorporating SCM along with CRCA has a significant effect on the compressive strength of concrete after 1 day and 28 days. The addition of 20% CRCA and 20% SCM appears to have a significant effect on the freeze-thaw durability of concrete. The experimental findings, when combined with the statistical analysis, provide compelling evidence to support the use of CRCA and SCM in concrete mixtures for the production of ICPs.

5.2 Contribution

This study focuses on developing sustainable ICPs for high-traffic urban areas. As seen from literature review, life cycle impact assessment confirmed the benefit of using SCM to replace Portland cement in concrete design. Although the energy required to process CRCA has a negative environmental impact, using CRCA is a possible solution to the problem of NA consumption. The sustainable concrete mixture designs were proposed based on total energy consumption and climate change impact results. The laboratory tests were carried out in terms of fresh and hardened performances, and the outcomes were encouraging.

Overall, the findings of this study suggest that CRCA and SCM applications in interlocking concrete pavements can significantly contribute to the reduction of NA consumption and CO_2 emissions.

5.3 Recommendations and Future Work

- In this study, the properties of three concrete mixes were tested out of the eight selected mixes, and these mixes performed adequately under the majority of the identified performance tests. However, laboratory tests for the remaining five mixes are required to determine the optimum mix design for sustainable ICPs.

- This study focuses on laboratory results to better understand the performance of ICPs containing CRCA and SCMs. At the same time, previous research (Omidi 2021) used FEM to simulate field conditions to evaluate the performance of these ICPs. However, field performance evaluation is recommended for practical purposes to fully understand the performance of these ICPs.
- According to the literature, using carbon curing techniques results in a 5% reduction in cement content, which results in a 25% reduction in CO_2 emissions (Achebe J. , 2020). The use of carbon curing techniques can result in more sustainable concrete, and further research into carbon curing is recommended.
- More research needs to be conducted to predict the propagation of fatigue cracks in ICPs subjected to cyclic loading.

References

1. Achebe, J. (2020). *Preliminary Environment Performance of New Concrete Pavement Design for Sidewalk labs Project.*

2. Achebe, J. C. (2021). Incorporating Environmental Sustainability into Pavement Design and Management.

3. Al-Bayati, H. K. (2019). Evaluation of Various Treatment Methods for Enhancing the Properties of Recycled Concrete Aggregate for Hot Mix Asphalt. Retrieved from http://hdl.handle.net/10012/14579

4. Association, C. P. (2020). Canadian Portland Cement Association. *Carbon footprint*. Retrieved from https://www.cement.org/docs/default-source/th-paving-pdfs/sustainability/carbon-foot-print.pdf

5. Barber, J. &. (1979). *The behaviour of a concrete block pavement.* ICE Publishing.

6. Beaty, A. a. (1992). Geotechnical aspects of interlocking concrete block pavements. (pp. 41-1/41-7). Proceedingd of 45th Canadian Geotechnical Conference.

7. Canada, S. (2021). *Satistics Canada*. Retrieved from https://www.statcan.gc.ca/en/start

8. Delatte, N. J. (2014). *Concrete Pavement Design, Construction, and Performance.* Boca Raton: CRC Press. doi:https://doi.org/10.1201/b17043

9. Hasanan Bin Md Nor, C. R. (2006). *The Effect Of Thickness and Laying Pattern of Paver on Concrete Block Paver.* Malaysia.

10. Pickel, D. (2014). Recycled Concrete Aggregate: Influence of Aggregate Pre-Saturation And Curing Conditions on The Hardened Properties of Concrete.

11. Shackel.B. (1980). *An Experimental Investigation of the Response of Interlocking Concrete Block Paving to Simulated Traffic Loading.* Aust Road Research Rpt 90.

12. Adetukasi, Adesola. 2020. "Shrinkage Deformation of Concrete Containing Recycled Coarse Aggregate." (January 2014).
13. Afroughsabet, Vahid, and Togay Ozbakkaloglu. 2015. "Mechanical and Durability Properties of High-Strength Concrete Containing Steel and Polypropylene Fibers." Construction and Building Materials 94: 73–82.
14. Ahmed, Tuqa Waleed, Ahmed A.Mohammed Ali, and Roua Suhail Zidan. 2020. "Properties of High Strength Polypropylene Fiber Concrete Containing Recycled Aggregate." Construction and Building Materials 241.
15. Ann, K. Y., H. Y. Moon, Y. B. Kim, and J. Ryou. 2008. "Durability of Recycled Aggregate Concrete Using Pozzolanic Materials." Waste Management 28(6): 993–99.
16. Association, Canadian Standard. 2006. 14 Precast Concrete Paving Slabs/Precast Concrete Pavers.
17. Bao, Jiuwen et al. 2020. "Influence of the Incorporation of Recycled Coarse Aggregate on Water Absorption and Chloride Penetration into Concrete." Construction and Building Materials 239.
18. Blazy, Julia, and Rafał Blazy. 2021. "Polypropylene Fiber Reinforced Concrete and Its Application in Creating Architectural Forms of Public Spaces." Case Studies in Construction Materials 14.
19. Bolat, Hakan et al. 2014. "The Effects of Macro Synthetic Fiber Reinforcement Use on Physical and Mechanical Properties of Concrete." Composites Part B: Engineering 61: 191–98.
20. Bravo, M., J. de Brito, L. Evangelista, and J. Pacheco. 2018. "Durability and Shrinkage of Concrete with CDW as Recycled Aggregates: Benefits from Superplasticizer's Incorporation and Influence of CDW Composition." Construction and Building Materials 168: 818–30.
21. Butler, Liam, Jeffrey S. West, and Susan L. Tighe. 2013. "Effect of Recycled Concrete Coarse Aggregate from Multiple Sources on the Hardened Properties of

Concrete with Equivalent Compressive Strength." Construction and Building Materials 47: 1292–1301.

22. Cahyani, R. A.T., and Y. Rusdianto. 2021. "An Overview of Behaviour of Concrete with Granulated Blast Furnace Slag as Partial Cement Replacement." In IOP Conference Series: Earth and Environmental Science, IOP Publishing Ltd.
23. Çakir, O. 2014. "Experimental Analysis of Properties of Recycled Coarse Aggregate (RCA) Concrete with Mineral Additives." Construction and Building Materials 68: 17–25.
24. Canadian Standards Association. 2019. CSA A23.2-5C Slump of Concrete.
25. Chakradhara Rao, M. 2018. "Properties of Recycled Aggregate and Recycled Aggregate Concrete: Effect of Parent Concrete." Asian Journal of Civil Engineering 19(1): 103–10.
26. Chorzepa, Mi Geum, and Mahadi Masud. 2017. "Performance of Multiscale, Including Nanoscale, Fibres in Concrete." Emerging Materials Research 6(1): 198–209.
27. Chua, Koon Meng, Zehra Askree, and Brian Shackel. 2000. "Axisymmetric Finite Element Modeling of Block Pavement Subjected to Repeated Loading." (00).
28. CSA A231.1/A231.2. 2006. 14 Precast Concrete Paving Slabs/Precast Concrete Pavers.
29. Duan, Zhen Hua, and Chi Sun Poon. 2014. "Properties of Recycled Aggregate Concrete Made with Recycled Aggregates with Different Amounts of Old Adhered Mortars." Materials and Design 58: 19–29.
30. El-Newihy, A., P. Azarsa, R. Gupta, and A. Biparva. 2018. "Effect of Polypropylene Fibers on Self-Healing and Dynamic Modulus of Elasticity Recovery of Fiber Reinforced Concrete."
31. Etxeberria, M, E Vázquez, A Marí, and M Barra. 2007. "Influence of Amount of Recycled Coarse Aggregates and Production Process on Properties of Recycled Aggregate Concrete." 37: 735–42.

32. Fonseca, N, J De Brito, and L Evangelista. 2011. “Cement & Concrete Composites The Influence of Curing Conditions on the Mechanical Performance of Concrete Made with Recycled Concrete Waste.” Cement and Concrete Composites 33(6): 637–43. http://dx.doi.org/10.1016/j.cemconcomp.2011.04.002.
33. Gagné, R. 2016. Science and Technology of Concrete Admixtures Air Entraining Agents. Elsevier Ltd.
34. Gao, Qi, Zhiming Ma, Jianzhuang Xiao, and Fuan Li. 2018. “Effects of Imposed Damage on the Capillary Water Absorption of Recycled Aggregate Concrete.” Advances in Materials Science and Engineering 2018.
35. Garilli, Erika, Federico Autelitano, Riccardo Roncella, and Felice Giuliani. 2020. “The Influence of Laying Patterns on the Behaviour of Historic Stone Pavements Subjected to Horizontal Loads.” Construction and Building Materials 258.
36. Gencel, O., C. Ozel, W. Brostow, and G. Martínez-Barrera. 2011. “Mechanical Properties of Self-Compacting Concrete Reinforced with Polypropylene Fibres.” Materials Research Innovations 15(3): 216–25.
37. Gokce, A., S. Nagataki, T. Saeki, and M. Hisada. 2004. “Freezing and Thawing Resistance of Air-Entrained Concrete Incorporating Recycled Coarse Aggregate: The Role of Air Content in Demolished Concrete.” Cement and Concrete Research 34(5): 799–806.
38. Hao, Lucen et al. 2018. “Effect of Salty Freeze-Thaw Cycles on Durability of Thermal Insulation Concrete with Recycled Aggregates.” Construction and Building Materials 189: 478–86.
39. Hwang, Jun Phil, Hyun Bo Shim, Sooyoung Lim, and Ki Yong Ann. 2013. “Enhancing the Durability Properties of Concrete Containing Recycled Aggregate by the Use of Pozzolanic Materials.” 17: 155–63.
40. I. Markovic. High-Performance Hybrid-Fibre Concrete.
41. Ismail, Sallehan, and Mahyuddin Ramli. 2013. “Engineering Properties of Treated Recycled Concrete Aggregate (RCA) for Structural Applications.” Construction and

Building Materials 44: 464–76. http://dx.doi.org/10.1016/j.conbuildmat.2013.03.014.

42. Jain, Jitendra, Kho Verian, Jan Olek, and Nancy Whiting. 2012. “Durability of Pavement Concretes Made with Recycled Concrete Aggregates.” Transportation Research Record (2290): 44–51.
43. Karahan, Okan, and Cengiz Duran Atiş. 2011. “The Durability Properties of Polypropylene Fiber Reinforced Fly Ash Concrete.” Materials and Design 32(2): 1044–49.
44. Khatib, J. M., and J. J. Hibbert. 2005. “Selected Engineering Properties of Concrete Incorporating Slag and Metakaolin.” Construction and Building Materials 19(6): 460–72.
45. Kou, Shi Cong, Chi Sun Poon, and Francisco Agrela. 2011. “Comparisons of Natural and Recycled Aggregate Concretes Prepared with the Addition of Different Mineral Admixtures.” Cement and Concrete Composites 33(8): 788–95.
46. Kou, Shi Cong, Chi Sun Poon, and Miren Etxeberria. 2014. “Residue Strength, Water Absorption and Pore Size Distributions of Recycled Aggregate Concrete after Exposure to Elevated Temperatures.” Cement and Concrete Composites 53: 73–82.
47. Krstic, Marija, and Julio F. Davalos. 2019. “Field Application of Recycled Glass Pozzolan for Concrete.” ACI Materials Journal 116(4): 123–31.
48. Kwan, Wai Hoe, Mahyuddin Ramli, Kenn Jhun Kam, and Mohd Zailan Sulieman. 2012. “Influence of the Amount of Recycled Coarse Aggregate in Concrete Design and Durability Properties.” Construction and Building Materials 26(1): 565–73.
49. Liu, Bing, Chao Feng, and Zhiheng Deng. 2019. “Shear Behavior of Three Types of Recycled Aggregate Concrete.” Construction and Building Materials 217: 557–72.
50. Liu, Hao et al. 2020. “Effect of SCMs on the Freeze-Thaw Performance of Iron-Rich Phosphoaluminate Cement.” Construction and Building Materials 230: 117012.
51. Mahdil, Zainab H., Baydaa Hussain Maula, Ahmed S. Ali, and Mass R. Abdulghani. 2019. “Influence of Sand Size on Mechanical Properties of Fiber Reinforced Polymer Concrete.” Open Engineering 9(1): 554–60.

52. Maruyama, Ippei. 2014. “A Trial of Reducing Autogenous Shrinkage by Recycled Aggregate A TRIAL OF REDUCING AUTOGENOUS SHRINKAGE BY.” (January 2005).
53. Mcneil, Katrina, and Thomas H Kang. 2013. “Recycled Concrete Aggregates : A Review.” 7(1): 61–69.
54. Ben Nakhi, Ammar, and Jasem M. Alhumoud. 2019. “Effects of Recycled Aggregate on Concrete Mix and Exposure to Chloride.” Advances in Materials Science and Engineering 2019.
55. Niaounakis, Michael. 2006. Wetlands Biopolymers: Applications and Trends.
56. Oikonomou, Nik D. 2005. “Recycled Concrete Aggregates.” 27: 315–18.
57. Oliveira, L A Pereira De. 2008. “Mechanical and Durability Properties of Concrete with Ground Waste Glass Sand.” (May).
58. Olofinnade, Oluwarotimi M, Julius M Ndambuki, and Anthony N Ede. 2017. “Application of Waste Glass Powder as a Partial Cement Substitute towards More Application of Waste Glass Powder as a Partial Cement Substitute towards More Sustainable Concrete Production.” (June): 19–20.
59. Omidi, Mahshad. 2021. “Development of a New and Innovative Concrete Paver.”
60. Omran, Ahmed, Nancy Soliman, Ablam Zidol, and Arezki Tagnit-Hamou. 2018. “Performance of Ground-Glass Pozzolan as a Cementitious Material-a Review.” Advances in Civil Engineering Materials 7(1): 237–70.
61. Oner, A., and S. Akyuz. 2007. “An Experimental Study on Optimum Usage of GGBS for the Compressive Strength of Concrete.” Cement and Concrete Composites 29(6): 505–14.
62. Ozawa, Mitsuo, Sirjana Subedi Parajuli, Yuichi Uchida, and Bo Zhou. 2019. “Preventive Effects of Polypropylene and Jute Fibers on Spalling of UHPC at High Temperatures in Combination with Waste Porous Ceramic Fine Aggregate as an Internal Curing Material.” Construction and Building Materials 206: 219–25.
63. Padmini, A. K., K. Ramamurthy, and M. S. Mathews. 2009. “Influence of Parent

Concrete on the Properties of Recycled Aggregate Concrete." Construction and Building Materials 23(2): 829–36.

64. Paranavithana, Sumeda, and Abbas Mohajerani. 2006. "Effects of Recycled Concrete Aggregates on Properties of Asphalt Concrete." Resources, Conservation and Recycling 48(1): 1–12.
65. Parron-Rubio, María Eugenia et al. 2019. "Slag Substitution as a Cementing Material in Concrete: Mechanical, Physical and Environmental Properties." Materials 12(18).
66. Patel, Dixit N., and Jayeshkumar R. Pitroda. 2013. "A Critical Literarure Review on Utilisation of Used Foundry Sand in Interlocking Paver Blocks." International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development (IJCSEIERD) 3(5): 157–66. http://www.tjprc.org/view_archives.php?year=2013_14_2&id=11&jtype=2&page=6.
67. Pietrzak, Alina, and Małgorzata Ulewicz. 2018. "The Effect of the Addition of Polypropylene Fibres on Improvement on Concrete Quality." In MATEC Web of Conferences, EDP Sciences.
68. Poon, Chi Sun, and Dixon Chan. 2007. "The Use of Recycled Aggregate in Concrete in Hong Kong." Resources, Conservation and Recycling 50(3): 293–305.
69. Qureshi, Liaqat Ali, Babar Ali, and Asad Ali. 2020. "Combined Effects of Supplementary Cementitious Materials (Silica Fume, GGBS, Fly Ash and Rice Husk Ash) and Steel Fiber on the Hardened Properties of Recycled Aggregate Concrete." Construction and Building Materials 263: 120636.
70. Rada, By Gonzalo R et al. 1991. "Structural Design of Concrete Block Pavements." 116(5): 615–35.
71. Rahal, Khaldoun. 2017. "Shear Strength of Recycled Aggregates Concrete." In Procedia Engineering, Elsevier Ltd, 105–8.
72. Ramesh, B, V Gokulnath, and M Ranjith Kumar. 2019. "Materials Today : Proceedings Detailed Study on Flexural Strength of Polypropylene Fiber Reinforced Self-Compacting Concrete." Materials Today: Proceedings (xxxx).

https://doi.org/10.1016/j.matpr.2019.11.292.

73. Rao, M. Chakradhara, Sriman Kumar Bhattacharyya, and Sudhirkumar V. Barai. 2019. Systematic Approach of Characterisation and Behaviour of Recycled Aggregate Concrete Systematic Approach of Characterisation and Behaviour of Recycled Aggregate Concrete Chapter 2.
74. Richardson, Alan, Kathryn Coventry, and Jennifer Bacon. 2011. "Freeze/Thaw Durability of Concrete with Recycled Demolition Aggregate Compared to Virgin Aggregate Concrete." Journal of Cleaner Production 19(2–3): 272–77.
75. Sagoe-Crentsil, K K, T Brown, and A H Taylor. Performance of Concrete Made with Commercially Produced Coarse Recycled Concrete Aggregate.
76. Said, Shwan H., and Hashim Abdul Razak. 2015. "The Effect of Synthetic Polyethylene Fiber on the Strain Hardening Behavior of Engineered Cementitious Composite (ECC)." Materials and Design 86: 447–57.
77. Saidani, Messaoud, Danah Saraireh, and Michael Gerges. 2016. "Behaviour of Different Types of Fibre Reinforced Concrete without Admixture." Engineering Structures 113: 328–34.
78. Sánchez, Marta, De Juan, and Pilar Alaejos. 2009. "Study on the Influence of Attached Mortar Content on the Properties of Recycled Concrete Aggregate." Construction and Building Materials 23(2): 872–77. http://dx.doi.org/10.1016/j.conbuildmat.2008.04.012.
79. Shao, Yixin, Thibaut Lefort, Shylesh Moras, and Damian Rodriguez. 2000. 30 Cement and Concrete Research Studies on Concrete Containing Ground Waste Glass.
80. Shayan, Ahmad, and Aimin Xu. 2004. "Value-Added Utilisation of Waste Glass in Concrete." Cement and Concrete Research 34(1): 81–89.
81. Shi, Caijun et al. 2016. "Performance Enhancement of Recycled Concrete Aggregate - A Review." Journal of Cleaner Production 112: 466–72.
82. Singh, Amanpreet, and Varinder Singh. 2019. "Performance of Glass-Powder Concrete in Field Applications." International Journal of Research VIII(III): 276–82.

83. Siva Chidambaram, R., and Pankaj Agarwal. 2015. "Seismic Behavior of Hybrid Fiber Reinforced Cementitious Composite Beam-Column Joints." Materials and Design 86: 771–81.
84. Soldado, Eliana et al. 2021. "Influence of Pozzolan, Slag and Recycled Aggregates on the Mechanical and Durability Properties of Low Cement Concrete." Materials 14(15).
85. Tam, V. W.Y., X. F. Gao, and C. M. Tam. 2006. "Comparing Performance of Modified Two-Stage Mixing Approach for Producing Recycled Aggregate Concrete." Magazine of Concrete Research 58(7): 477–84.
86. Tam, Vivian W.Y., Mahfooz Soomro, and Ana Catarina Jorge Evangelista. 2018. "A Review of Recycled Aggregate in Concrete Applications (2000–2017)." Construction and Building Materials 172: 272–92.
87. Tam, Vivian W Y, X F Gao, and C M Tam. 2005. "Microstructural Analysis of Recycled Aggregate Concrete Produced from Two-Stage Mixing Approach." 35: 1195–1203.
88. Tanyildizi, Harun. 2009. "Statistical Analysis for Mechanical Properties of Polypropylene Fiber Reinforced Lightweight Concrete Containing Silica Fume Exposed to High Temperature." Materials and Design 30(8): 3252–58.
89. Tavakoli, H.R, Omid Lotfi Omran, Masoud Falahtabar Shiade, and Saman Soleimani Kutanaei. 2014. "Download." Latin Ameraican journal of solids and structures: 1906–23. https://www.scielo.br/j/lajss/a/4Tq7WyYdhg66nH5p777HZdf/?lang=en.
90. Tiwari, Prafulla Kumar, and Raman Nateriya. 2016. International Journal of Scientific Engineering and Applied Science (IJSEAS) Replacement of Recycled Coarse Aggregates with Natural Coarse Aggregates in Concrete. www.ijseas.com.
91. Vaitkus, Audrius et al. 2019. "Concrete Modular Pavements - Types, Issues and Challenges." Baltic Journal of Road and Bridge Engineering 14(1): 80–103.
92. Wang, Dehong, Yanzhong Ju, Hao Shen, and Libin Xu. 2019. "Mechanical Properties of High Performance Concrete Reinforced with Basalt Fiber and Polypropylene Fiber." Construction and Building Materials 197: 464–73.

https://doi.org/10.1016/j.conbuildmat.2018.11.181.

93. Wong, Yiik Diew, Darren Delai Sun, and Dickson Lai. 2007. “Value-Added Utilisation of Recycled Concrete in Hot-Mix Asphalt.” 27: 294–301.
94. Xiao, Jianzhuang. 2018. Springer Tracts in Civil Engineering Recycled Aggregates.
95. Yang, Keun Hyeok, Heon Soo Chung, and Ashraf F. Ashour. 2008. “Influence of Type and Replacement Level of Recycled Aggregates on Concrete Properties.” ACI Materials Journal 105(3): 289–96.
96. Yap, Soon Poh et al. 2014. “Flexural Toughness Characteristics of Steel-Polypropylene Hybrid Fibre-Reinforced Oil Palm Shell Concrete.” Materials and Design 57: 652–59.
97. Yehia, Sherif et al. 2015. “Strength and Durability Evaluation of Recycled Aggregate Concrete.” International Journal of Concrete Structures and Materials 9(2): 219–39.
98. Zaharieva, Roumiana. 2004. “Frost Resistance of Recycled Aggregate Concrete.” 34: 1927–32.
99. Zhang, Peng, and Qing Fu Li. 2013. “Effect of Polypropylene Fiber on Durability of Concrete Composite Containing Fly Ash and Silica Fume.” Composites Part B: Engineering 45(1): 1587–94.

Appendix

Single Factor Annova test for compressive strength of CM and RC 20 mix to identify the statistical significance of 20 % CRCA in the concrete mix.

1 day

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	51	17	1
Column 2	3	56	18.66667	0.333333

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.166667	1	4.166667	6.25	0.066767	7.708647
Within Groups	2.666667	4	0.666667			
Total	6.833333	5				

7 Days

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	98	32.66667	2.333333
Column 2	3	96	32	3

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.666666667	1	0.666667	0.25	0.64333	7.708647
Within Groups	10.66666667	4	2.666667			
Total	11.33333333	5				

28 Days

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	120	40	4
Column 2	3	115	38.33333	0.333333

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.166667	1	4.166667	1.923077	0.237796	7.708647
Within Groups	8.666667	4	2.166667			
Total	12.83333	5				

Single Factor Annova test for absorption of CM and RC 20 mix to identify the statistical significance of 20 % CRCA in concrete mix.

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	13.56	4.52	0.0403
Column 2	3	10.99	3.663333	0.488233

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.100817	1	1.100817	4.165552	0.110822	7.708647
Within Groups	1.057067	4	0.264267			
Total	2.157883	5				

Single Factor Annova test for tensile strength of CM and RC 20 mix to identify the statistical significance of 20 % CRCA in concrete mix.

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	14.29936	4.766454	0.00047
Column 2	3	14.17516	4.725053	0.001464

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.002571	1	0.002571	2.659091	0.178294	7.708647
Within Groups	0.003868	4	0.000967			
Total	0.006439	5				

Single Factor Annova test for shear strength of CM and RC 20 mix to identify the statistical significance of 20 % CRCA in concrete mix.

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	2	11.45	5.725	0.00125
Column 2	2	11.35	5.675	0.00245

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0025	1	0.0025	1.351351	0.364999	18.51282
Within Groups	0.0037	2	0.00185			
Total	0.0062	3				

Single Factor Annova test for freeze-thaw durability of CM and RC 20 mix to identify the statistical significance of 20 % CRCA in concrete mix.

Loss of Mass 7 days

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	166	55.33333	9.333333
Column 2	3	278.8	92.93333	9.013333

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2120.64	1	2120.64	231.1744	0.000109	7.708647
Within Groups	36.69333	4	9.173333			
Total	2157.333	5				

Loss of Mass 28 days

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	333.8	111.2667	585.6933
Column 2	3	362.8	120.9333	575.0233

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	140.1667	1	140.1667	0.241517	0.648858	7.708647
Within Groups	2321.433	4	580.3583			
Total	2461.6	5				

Total Loss of Mass

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	499.8	166.6	667.96
Column 2	3	641.6	213.8667	720.1433

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3351.207	1	3351.207	4.828469	0.092924	7.708647
Within Groups	2776.207	4	694.0517			
Total	6127.413	5				

Single Factor Annova test for compressive strength of RC 20 and RC 20/S 20 mix to identify the statistical significance of 20 % SCM in concrete mix.

<u>1 day</u>

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	4	73	18.25	0.916667
Column 2	4	59	14.75	0.916667

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	24.5	1	24.5	26.72727	0.002075	5.987378
Within Groups	5.5	6	0.916667			
Total	30	7				

<u>7 days</u>

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	4	125	31.25	4.25
Column 2	4	116	29	4.666667

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10.125	1	10.125	2.271028	0.182533	5.987378
Within Groups	26.75	6	4.458333			
Total	36.875	7				

28 days

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	115	38.33333	0.333333
Column 2	3	119	39.66667	0.333333

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.666667	1	2.666667	8	0.047421	7.708647
Within Groups	1.333333	4	0.333333			
Total	4	5				

Single Factor Annova test for absorption of RC 20 and RC 20/S 20 mix to identify the statistical significance of 20 % SCM in concrete mix.

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	0.1099	0.036633	4.88E-05
Column 2	3	0.1192	0.039733	1.34E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.44E-05	1	1.44E-05	0.463306	0.533444	7.708647
Within Groups	0.000124	4	3.11E-05			
Total	0.000139	5				

Single Factor Annova test for tensile strength of RC 20 and RC 20/S 20 mix to identify the statistical significance of 20 % SCM in concrete mix.

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	14.17516	4.725053	0.001464
Column 2	3	13.94586	4.64862	0.012073

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.008763	1	0.008763	1.294705	0.318712	7.708647
Within Groups	0.027073	4	0.006768			
Total	0.035836	5				

Single Factor Annova test for shear strength of RC 20 and RC 20/S 20 mix to identify the statistical significance of 20 % SCM in concrete mix.

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	2	11.35	5.675	0.00245
Column 2	2	11.42222	5.711111	0.0032

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.001304	1	0.001304	0.461597	0.566965	18.51282
Within Groups	0.00565	2	0.002825			
Total	0.006954	3				

Single Factor Annova test for freeze-thaw durability of RC 20 and RC 20/S 20 mix to identify the statistical significance of 20 % SCM in concrete mix.

Loss of Mass 7 days

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	278.8	92.93333	9.013333
Column 2	3	45	15	7

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	9110.407	1	9110.407	1137.853	4.61E-06	7.708647
Within Groups	32.02667	4	8.006667			
Total	9142.433	5				

Loss of Mass 28 days

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	362.8	120.9333	575.0233
Column 2	3	166.2	55.4	5.76

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6441.927	1	6441.927	22.18358	0.00924	7.708647
Within Groups	1161.567	4	290.3917			
Total	7603.493	5				

Total loss of Mass

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	3	641.6	213.8667	720.1433
Column 2	3	211.2	70.4	0.76

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	30874.03	1	30874.03	85.65372	0.000758	7.708647
Within Groups	1441.807	4	360.4517			
Total	32315.83	5				