EQUIVALENT CO_2 EMISSIONS AND CONSTRUCTION COSTS OF BUILDINGS DESIGNED USING RECYCLED AGGREGATE CONCRETE

Sarp Olcun

A Thesis Submitted to The Faculty of Graduate Studies in Partial Fulfillment of The Requirements for The Degree of Master of Applied Science

MASc. Graduate Program in Civil Engineering York University Toronto, Ontario

February 2023

ABSTRACT

Growing environmental concerns and lack of a sustained source of aggregate resources, have resulted in increased research dedicated to concrete produced with a variety of recycled and secondary materials. Despite the environmental benefits of recycled concrete aggregate (RCA), compared with conventional aggregates, the use of these materials often results in significantly lower mechanical properties of the resulting RCA concrete, requiring increases in cement content or structural dimensions in order to obtain similar strengths. In order to quantify and better understand environmental benefits of RCA concrete, a series of hypothetical case study structures were designed and analysed for equivalent CO_2 emissions and costs during construction. In cases where higher quality RCA was available the reduction in eCO_2 emissions was determined to be as high as 13.7%. Even with lower quality RCA, emission reductions of up to 8% were observed with certain alterations to structural design. It was concluded that when utilizing RCA concrete in new construction, the quality of the material available was the main factor in determining the degree of reduction in eCO_2 emissions and the costs. Additional areas of further research were determined including more Lifecycle Assessment impact categories, RCA concrete structure assessment throughout service life, and analysis of additional building types.

STATEMENT OF CONTRIBUTIONS

The following published and in-progress contributions have resulted from the research work presented in this thesis:

Raut S, Olcun S, Butler LJ (2023). Evaluating the use of limestone calcined clay cement and recycled concrete aggregates for reducing the carbon footprint of concrete structures. 2nd International Construction Materials and Structures (ICCMS), held virtually, December 14 – 18, 2022.

Olcun S, Santorsola J, and Butler LJ (2021). Design and trade-off optimization for reduction of carbon emissions in concrete structures using recycled materials. FIB Symposium Proceedings, Lisbon, Portugal., 14 – 16, June 2021.

Olcun S and Butler LJ (2023). Quantification and Optimization of Total Equivalent CO2 Emissions in Buildings Designed Using Recycled Aggregate Concrete. (Journal Paper In-progress)

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my supervisor, Dr Liam Butler, who has been extremely supportive, encouraging, and knowledgeable throughout this project, and provided me with this great opportunity.

Im also grateful for the time and effort that Dr. John Gales and Dr. Mojgan Jadidi have taken to serve as my committee members and examiners.

Words cannot express my gratitude to my parents Gulin and Sami, as well as my brother Sinan for there endless motivation and support throughout this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: Introduction

1.1 Overview

This chapter gives an overall introduction to the research project being undertaken along with some background information. The first section provides details on natural aggregate concrete, highlighting the importance of the material to the construction industry and problems associated with its use. Following this, an overview of the significance of the research is provided along with the main research objectives and the organization of the thesis.

1.2 Background

In the 21st century, the construction industry has become a significant influence in the world socially, economically, and environmentally. As populations grow and the needs of communities around the world shift, there will be increased reliance on the industry to provide services and products utilised everyday. The scale of the economic contribution from construction can be seen by looking at the GDP of developed and developing nations throughout the world and what portion of it is generated by the projects undertaken in the industry. With the European Union and Canada, studies performed in the past decade have demonstrated that the construction industry was responsible for 6% and 9% respectively (Statistics Canada 2012, European Commission 2017). Further, construction is also one of the most significant sources of employment globally accounting for 7.3% of all jobs in Canada and 18 million jobs in the European Union. With the economic and social importance of the construction industry, there is constant growth often out pacing other industries meaning that any issues that may arise will be amplified in the future (Statistics Canada 2012, European Commission 2017). Although the size and rapid growth of the industry may be overwhelming, it is often beneficial to society as the industry provides essential infrastructure and services that communities rely on heavily. Only through the construction of new buildings such as hospitals, schools, housing, and power plants at an increasing rate can the world keep up with the demand for rapid urbanization. However, it is extremely important to consider the cost of these types of projects both economically and environmentally. As the size of the construction sector increases with the demand for new infrastructure, non-renewable resources will be consumed and pollution caused by related activities will rise rapidly over time (Baccini 1997). When trying to understand the environmental influence of the construction industry, the production and the use of concrete is one of the main concerns as it is the most widely used material in the world. One of the reasons for this is the massive scale at which the material is consumed globally every year. A popular statistic that illustrates the issue is the fact that concrete is the second most consumed material in the world at 33 billion tons produced every year only surpassed by water (International Organization for Standardization 2005).

As the volume of concrete produced globally is very large, any impact the process my have on the environment is greatly amplified. In addition to the carbon emissions caused by the processes involved in production, the construction of buildings with concrete also requires the consumption of many natural resources such as the minerals found in cement, quarried stones, and water. To understand the environmental problems posed by concrete production, it is important to review the constituents of the material and the details of the manufacturing process. The typical materials used in the production of concrete are Portland cement powder, water, coarse aggregates, and fine aggregates. As the material mainly responsible for the strength of concrete, Portland cement is also the material that is the most harmful for the environment in the process. This is due to the fact that the production of cement powder generates large amounts of green house gases both from the energy requirements of the clinkering process as well as the chemical processes involved which release carbon dioxide into the atmosphere.

The second largest contributor to the environmental impact of concrete production is the mining and transportation of coarse and fine aggregates from quarries to the concrete batching site. Depending on the location of concrete aggregate quarries in relation to the site, the greenhouse gas emissions generated by the transportation of materials can surpass those of mining and manufacturing. The transportation scenarios seen in the production of concrete aggregates can change significantly between different countries along with the availability of aggregate resources. In the Greater Toronto Area for example, there are many aggregate quarries that can provide concrete batching plants with the necessary materials some of them within 25 km of the downtown core. However, this level of aggregate availability is not always possible in every city around the world. For example, a study performed in Shanghai, one of the largest and most developed cities in China, required aggregates for use in concrete to be transported extremely large distances. Concrete aggregates that were used in the construction of mid-rise buildings had to be transported from a quarry 200 km away using both heavy trucks and shipped over a large body of water (Xiao et al. 2018). With concrete aggregates, the use of material transported such long distances is significantly amplified by the large volume that is required in the construction of buildings. With aggregate shipping distances increasing and the weight of material required to supply the development of urban areas increasing rapidly, the corresponding impact on the environment must be carefully monitored. These impacts are already being reported in Ontario where the consumption to replacement ratio of aggregates rose to 2.5 in 2009, within the largest urban center (i.e., Toronto) with only half of aggregates used in construction produced locally (Ontario Ministry of Natural Resources 2010).

Another impact of the consumption of concrete in the construction industry becomes apparent for buildings when approaching the end of their service life. As structures are not built to be permanent, at some point they will have to be decommissioned and all materials used will have to be disposed of. With the use of materials such as steel, through the recycling of demolition waste, the materials which were spent during construction can be recycled and reused. However, with the current approach that has been adopted in the construction industry most concrete waste typically ends up in landfills or in illegal disposal sites. The scale of this waste generation issue was reported in an EU study finding that almost 8% of all waste produced by member countries was from concrete from construction and demolition activities (Fischer and Werge 2009).

Considering the potential environmental impact of the continued construction of concrete infrastructure, there has recently been significant development of technologies aimed at improving its long-term sustainability. With the main issue being the carbon emissions generated during the cement production process, there have been many studies looking into the use of supplementary cementitious materials which are by-products of various other industrial processes (e.g., slag, silica fume, fly ash, etc.) as a partial replacement of ordinary Portland cement. Additionally, there has been growing interest and research in the field of alternative binder material such as limestone calcined clay and geopolymer cements attempting to bypass the emission heavy processes involved in Portland cement production (Błyszko 2017, Run-Sheng et. al. 2022). Considering the aggregates used in concrete, there has been a lot of research on the replacement of natural quarried stones with materials found either as by-products of other industries, or recycled construction and demolition waste (Butler et. al. 2014, Ding et. al. 2016). The aggregates typically used in the production of concrete are extracted from quarries which are then crushed and graded by size to be used in different construction applications. Instead of the quarried stones used in a conventional concrete, the aggregate phase can be replaced by different solid materials with similar mechanical properties (Gursel and Ostertag 2019). The main material used in this way has been hardened concrete or recycled concrete aggregates (RCA) which is diverted from the construction and demolition waste stream to be used in the production of new concrete (i.e., RCA concrete). This process effectively provides a method of recycling concrete and moves the construction industry as a whole towards a more sustainable approach to concrete construction. With varying levels of natural aggregate replaced with these RCAs, studies have shown that RCA concrete produced can achieve similar mechanical properties as those of conventional concrete (Xiao et al. 2018, Fahmy and Idriss 2019). Assuming that the level of concrete waste generated globally is similar to the EU (8% of all solid waste), this type of concrete recycling could be a significant intervention for reducing waste generation as well as improving the availability of aggregates for the construction of new buildings. However, it is important to consider issues that arise with the use of RCA in concrete such as the presence of deleterious brick, plastic, and ceramic waste. As the construction and demolition processes that produce concrete waste often do not provide a way in which materials can be sorted during the work, the presence of these contaminants may impact the resulting concrete performance. Additionally, RCAs consists not only of natural aggregate materials but also particles of mortar that have been adhered to the surface of the aggregates produced. This adhered mortar does not have the desired level of strength found in natural aggregates and also increases the water absorption of the material (Butler et. al. 2014, Hanif 2020). When mixing new concrete, this increased water adsorption will result in locally higher water-cement ratios in the interfacial transition zone further reducing the strength of the concrete produced (Hanif 2020). Through a review of currently available literature on RCA concrete properties, it was found that on average, there is a strength loss of 11.2% to 14.7% for concrete grades of 20-60 MPa (Appendix A for references). In addition to changes in compressive strength, the use of RCA often result in alterations to durability properties such as an increased propensity for chloride ingress and creep. These issues resulting in inferior mechanical properties in RCA concrete can often be alleviated through alterations to the mixture proportions such as increasing cement contents and incorporating different chemical admixtures. The quality of the RCAs can also be improved by secondary treatment procedures after crushing in order to enhance RCA concrete performance (Hanif 2020, Chinzorigt et al. 2020). Unfortunately, both of these solutions will impact both the economic cost and environmental impact of the material which might make it infeasible or counterproductive to the goal of sustainability.

By incorporating recycled concrete aggregates (RCA) into concrete production, there are multiple sustainability benefits that can be gained for the construction industry. One of the main advantages of RCAs is that the equivalent CO_2 emissions generated during their production is significantly lower compared to natural aggregates. Additionally, with the increased availability of material, carbon emissions can be further reduced by cutting transportation requirements in areas where natural aggregates are not produced locally (Ding, Xiao, and Tam 2016, Xiao et al. 2018). The recycling of concrete also reduced the reliance of the construction industry on natural aggregates, increasing the longevity of the non-renewable resource. Further, as landfilling and illegal disposal of waste is a significant environmental and societal concern, the recycling of a large portion of this waste will be of great benefit.

1.3 Research Significance

With the potential sustainability benefits that are present with the use of RCAs, many studies have examined the use of this novel material in concrete production. However, if the adoption RCA in concrete production is to become common practice, it is essential that of its impact on the resulting concrete mechanical properties is fully understood. As most reinforced design codes and standards are based on empirical data collected over many years, an in-depth understanding of the behaviour of RCA concrete is also required. Multiple studies have already documented the alterations to mechanical properties such as compressive, tensile, and flexural strength cause by the addition of RCA to concrete (Butler et al. 2011, Chinzorigt et al. 2020, Evangelista and Brito 2007, Xiao et al. 2012). Since the use of RCA in concrete production can also have an impact on durability related properties such as chloride ingress, permeability, creep, and shrinkage, these properties have also been documented (Chinzorigt et al. 2020). Texture, shape, density, and adhered mortar are all properties that differ between natural and recycled aggregates and thus, have been documented by multiple researchers (Robu, Mazilu, and Deju 2017). Before adopting technologies that attempt to improve sustainability in any field, the existence of these potential benefits must be confirmed. Before the use of RCA become widespread, the environmental benefits that are present must be identified and quantified, both to confirm the effectiveness of the novel material and to increase awareness and willingness to adopt in the construction industry. As such, there have been many studies which have attempted to document the environmental benefits of RCA concrete such as reduced carbon emissions, natural resource conservation, and reduced waste generation in detail. This type of sustainability evaluation often takes the form of a life-cycle analysis (LCA) which records the inputs and outputs of a process to determine the environmental impact. In addition to use of LCA in research projects assessing environmental impact, it is also the standard used by the industry for the preparation of Environmental Product Declarations (EPD). These EPD documents produced by companies for demonstration of products, present the manufacturing impacts for products such as cement. As concrete is the most popular construction material, multiple academic studies and EPDs document the life-cycle analysis of concrete produced with natural aggregates (Fantilli et al. 2019, Eleftheriadis et al. 2018, He et al. 2019). Since RCA concrete is a relatively novel technology in the construction industry, there is limited documentation of the LCA of its production process (Knoeri et al.2013, Jiménez et al. 2018, Park et al. 2019, Pradhan et al. 2019, Visintin et al.2020). One area of interest where a gap in RCA research exists is the impact of the structural design process on the use of RCA concrete and its sustainability.

The purpose of this study is to address this gap in the research around RCA concrete through a desktop study to explore the effect of design on the use and eCO_2 footprint of this novel material. After quantifying the sustainability of the material, the main goal is to propose how the performance can be optimised for reduced carbon emissions by considering the trade-offs and benefits of the RCA concrete. A case study has been developed where multiple hypothetical medium-rise reinforced concrete buildings have been designed using various conventional and RCA concrete mixes. Looking mainly at the mechanical property of compressive strength at multiple levels of reduction due to the presence of RCA, designs were adjusted by increasing member dimensions and/or increasing steel reinforcement to compensate. The effects of further design changes such as changing from a flat plate to flat slab floor system, or selective use of RCA concrete in specific structural members were also evaluated. A detailed material inventory was constructed for each design considered with the carbon emission also documented. This data was used to judge the effectiveness of RCA in reducing eCO_2 emissions depending on each scenario to better understand how the practice can best improve sustainability in construction projects.

1.4 Research Objectives

When using RCA concrete in construction, as stated previously, there will be changes to the strength of the material. Depending on various factors such as transportation requirements, material quality, structural design and degree of RCA utilization, there can be increases or reductions to sustainability and costs. The main question of this research is; how do these factors influence each other and what kinds of decisions can lead to a design optimized for sustainability and costs? This is demonstrated in the main research objectives:

1. Develop a database of concrete mixes with corresponding carbon emissions per unit volume and strength reduction due to use of RCA.
2. Create an integrated design process for generating multiple structural design case scenarios with different grades of RCA concrete, structural floor systems, RCA utilization, and aggregate transportation scenarios.
3. Propose recommendations and strategies for optimizing design using RCA concrete for eCO_2 emissions and construction cost.

1.5 Thesis Organization

Excluding the introduction and conclusion chapters, this thesis has 6 main chapters corresponding to the different phases of the study. The first of these chapters is the Literature Review providing a summary of the most significant research papers reviewed throughout the course of this study and describing how they informed and/or connect to the work that was done. The following chapter on Research Methodology highlights how the study was structured and research objectives completed. The fourth chapter details how the structural design process used for the generation of material inventories for each scenario was carried out. The next chapter describes the pilot study which was performed with preliminary results and analysis as well as highlighting how this initial work lead to the construction of an RCA concrete database of mixes documented in literature. Chapter 6 explains the generation of the main scenarios examined for the study with analysis, discussion, and comparisons for each case considered. Finally, the last main chapter presents the estimated construction costs of each scenario with discussing how the effects of each aspect and provides example case studies for the optimization of costs and emissions.

CHAPTER 2: Literature Review

2.1 Overview

In this chapter, an overview of the literature reviewed is presented with a summary of the most relevant papers. At the beginning of this research project, the initial focus was on reviewing literature related to the use of RCA concrete and the material properties. This included papers highlighting the need for new aggregate resources, those evaluating mechanical and durability properties of RCA, and case studies on RCA concrete structures. To understand how RCA concrete and other materials are evaluated for sustainability the next focus of literature review was the Lifecycle Assessment (LCA) process. This included analysis of the history and practice of LCA, as well as the application of LCA in concrete mix and structure assessment. Finally, to better demonstrate the research gap, studies evaluating RCA concrete structure design and emissions simultaneously were examined.

2.2 Background

2.2.1 Issues With Natural Aggregate Production

In the pursuit of ecological sustainability, the most important factors to consider are the development of urban spaces and consumption of fossil fuels. This is highlighted in the 1997 paper "A City's Metabolism: Towards the Sustainable Development of Urban Systems" by Peter Baccini. In the paper, Baccini states that a model considering the transformation and movement of resources through urban regions is critical in moving towards sustainable development. This is reinforced by the fact that globally urban settlements consume between 70 and 80 percent of the world's resources. The study presents guidelines for the ecological sustainable development of an urban region including the use of 100% renewable resources, protection of biodiversity and limiting of pollution.

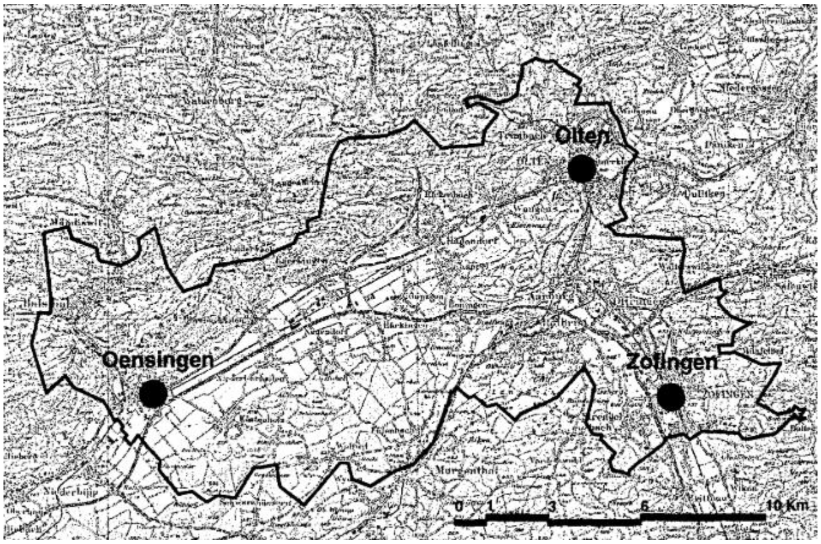


Figure 2-1:Study Area in the Swiss Lowlands

A look into the state of construction materials in the urban KSM region (presented in Figure 2-1) of the Swiss Lowlands focusing on gravel and sand mainly used in the manufacturing of concrete is included in the study. Baccini writes that although the stocks of aggregate material currently available would hold for several generations, the rate of renewal by natural processes is much lower than the rate of consumption (by 2-3 orders of magnitude). He reasons that for the region to achieve sustainability goals, alternative materials would be needed to replace natural gravel. This paper provided insight into how the unsustainable management of construction resources could potentially impede future development of an urban area. Although these materials can be imported from outside the region specified, this would have a significant ecological impact as the weight of material needed for concrete production would take more energy to transport (Baccini, 1997).

When considering the use of recycled materials in the production of concrete, it is important to understand why this practice is needed and the potential benefits. Studies on the availability of aggregates can help identify the issues that may arise from the depletion of this natural resource.

The 2010 (most recent) report produced by the Ontario Ministry of Natural resources provides useful local information regarding the future availability of aggregates and the need for increased recycling in the construction industry. The study found that the total aggregate consumption in Ontario for 2007 was 184 million tones including the 13 million tonnes provided by recycling which was expected to increase due to economic and population growth. The Greater Toronto Area alone consumes about a third of this amount with only half of the material produced locally. It is stated that through the use of recycled materials in the production of new concrete, land use, energy consumption, waste generation, and financial costs can be reduced. Further, it is explained that the consumption to replacement ratio of natural aggregates in the GTA has risen to 2.5 from 1991 and 2009, confirming that the aggregate resource is being rapidly depleted. The report concludes that a shift from the current “close to market” policy of aggregate resources to the transportation of materials from increasingly distant areas would have significant economic, environmental, and social impact (Ontario Ministry of Natural Resources, 2010).

Figure 2-2: Aggregate Reserves located within 75km of the GTA (Ontario Ministry of Natural Resources, 2010)

A study by Golder Associates Ltd. of the remaining aggregate resources in the greater golden horseshoe area support the findings of the Ontario Ministry of Natural Resources. In addition, the report highlights the uncertainty of the findings on the total availability of aggregates with current estimation procedures. This demonstrates the need to diversify aggregate sources to avoid unexpected shortages in the future. In 2009, a material supply analysis was performed by the Ontario Ministry of Natural resources. Although there is a large volume of materials to be extracted for use as aggregate in the greater golden horseshoe area, the presence of the appropriate grade aggregate resource for construction projects is not the only factor for material availability. There are multiple considerations such as competing land use and environmental protections that limit the amount of aggregates available for extraction. Of the aggregate resource areas examined in the study, between 92 and 96% overlapped with constraints making the extraction of natural aggregates difficult. The study prescribes a carefully planned approach to the consumption and production of aggregates as sustainability is a concern. Although materials can be sourced from further regions if there are shortages, the importance of close to market locations is highlighted as longer haul distances increase both costs and environmental impacts. While the main source of aggregates is expected to be extracted from pits and quarries over the next 20 years, the study also acknowledges the growing utilization of recycled aggregate materials as an alternative (Golder Associates, 2016).

With the continuous growth of natural aggregate consumption and the reduction in the available sources, the production of concrete will become more expensive and have increasing environmental impacts. As mentioned in the studies reviewed, the use of recycled aggregates is one of the strategies for reducing reliance on natural aggregate sources which has been used before in concrete production.

2.2.2 Emergence of RCA Concrete

After the events of World War II, there was an urgent need to manage waste from building rubble and produce aggregate for concrete construction to recover from damage to urban areas in much of Europe. During this time, one of the practices that helped with this process was the use of RCAs produced by crushing waste concrete to be used in new construction (Buck, 1976). In 1976, Buck discusses the re-emergence of the practice of recycling concrete which was largely abandoned. The study found that although the US had sufficient aggregate supplies to sustain development, these resources were becoming evermore scarce in urban regions. The paper goes into more detail about how much recyclable waste is available during writing and also the new equipment and practices developed for the demolition of aging infrastructure to be used in new concrete production. From limited laboratory and field testing available at the time Buck asserts that recycled concrete aggregates are adequate for the production of concrete. The main benefits highlighted include reduced waste generation from construction and demolition activity as well as energy conservation. The reduction is energy requirements is attributed mainly to the reduced transportation distances associated with the manufacturing of conventional aggregates versus RCA are very similar (Buck, 1976). As this specific study is over 50 years old, the review of more recent research should provide a better understanding of the current state of RCA concrete in the construction industry.

2.3 RCA Concrete Material Properties

2.3.1 Effect of RCA Use on Strength and Durability of Concrete

As concrete produced using recycled materials tends to possess inferior properties, it is important to understand the role of the RCA in contributing to this reduction in performance. One European study reviewed examined the properties of the recycled aggregates that lead to this poor behaviour and how these materials can be characterized. By crushing and grading samples of concrete cast for the study, the researchers produced aggregates of three different sizes which were compared to natural river aggregates. Upon measuring the density of the material produced, it was found that the recycled aggregates had noticeably lower density compared to the natural aggregate, further decreasing with increasing grain size. The water absorption of the recycled aggregates was also much higher due to the porous adhered mortar on the surface. The presence of the adhered mortar was also significant during the Los Angeles abrasion test since the recycled aggregates lost much more mass in the from of fine powdered mortar which detached during the experiment. The researchers concluded by explaining that the use of RCAs do not always lead to reduced mechanical properties, as the quality of the material used plays an important role. Specifically, the newly produced and crushed concrete performed better as an aggregate due to the presence of unhydrated cement paste, the rough surface texture, and the absence of contaminants (Robu et al., 2017).

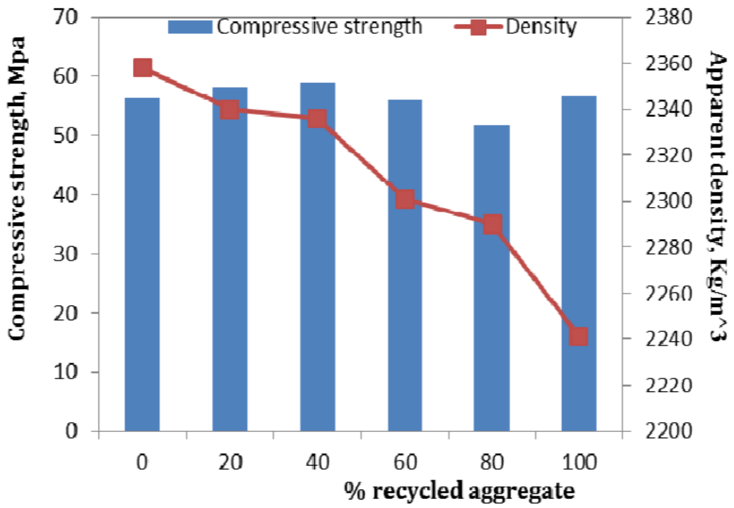


Figure 2-3: The variation of apparent density and compressive strength of concrete, depending on the proportion of recycled aggregate content (Robu et al., 2017)

Since RCAs are produced by crushing concrete from construction and demolition waste, it is important to understand the effect of the original concrete on the new mechanical properties. In a study by Bhat (2021), they examined 50 and 100% replacement of coarse aggregates with RCAs at the three compressive strength grades of 20, 40, and 60 MPa. It was found that the grade of the original concrete used in the production of RCA had no significant effect on the mechanical properties of the new material such as compressive, tensile, and flexural strength. As casting is also an important factor, Bhat (2021) considered the fresh properties of each mix and found that at saturated surface dry aggregate conditions, the slump was in the 80 to 100 mm range with no losses for RCA (Bhat, 2021).

As the use of recycled materials in concrete production is adopted into the construction industry, it is very important that the mechanical properties are well understood. It is also critical that the use of these new materials in explored in multiple different construction fields such as the pre-cast industry. In a 2019 study conducted by researchers in Egypt, the use of RCA concrete in the production of large pre-cast T-beams was investigated. The main focus of the study was to evaluate the performance of RCA concrete as a filler material in semi pre-cast beams where the core is cast inside a U-shaped high strength concrete section. Two different types of beam core were tested, with the RCA concrete placed either as a series of individual pre-cast blocks or cast monolithically along the length of the section. Upon testing, they observed that all beams failed in flexure with the cracking patterns depending on the grade of the RCA concrete filler used. In addition, the use of RCA concrete blocks as filler material in the core had a positive effect on the flexural properties with fewer cracks propagating into the beam flange (Fahmy and Idriss, 2019).

As the binder material used during the production of concrete is the greatest contributor to the environmental impact, many substitute materials have been proposed. These binder materials referred to as supplementary cementitious materials (SCMs) have seen increasing utilization in the construction industry. Therefore, it has become important that the interaction between RCA and SCMs is considered with respect to the properties of the concrete produced. One 2018 study examined the simultaneous use of these materials in evaluating the flexural behavior of large scale semi-precast reinforced concrete T-beams. The study investigated the incorporation f 100% coarse RCA into new concrete mixtures which also contained up to 30% of a variety of SCMs including, rice husk ash, palm oil fuel ash, and palm oil clinker powder. The study analyzed differences in compressive strength as well as durability related properties such as chloride penetration and electrical resistivity. It was found that with the use of the SCMs listed, the compressive strength of the mixes could be increased compared to the control mixes. Although the properties of the RCA concrete were inferior at 28 days, there were significant improvements in chloride ingress and resistivity at the age of 90 days due to the SCMs (Alnahhal et al., 2018).

To increase the use of RCA in the construction industry, more understanding is necessary in the classification of various aggregate sources. Since RCAs can result in detrimental effects with respect to mechanical properties, certain projects will need a framework for the identification of satisfactory aggregate sources. In a 2014 study, Butler et al. investigated the influence of fundamental aggregate properties on the performance of the resulting RCA concrete and proposed an RCA classification framework. To observe the effects of parent concrete, three different sources of RCA were evaluated. Crushed aggregates sourced from pavement and drainage structures, demolition waste from an airport with high quantities of deleterious materials, and hardened concrete returned to a ready-mix plant were used for 100% replacement of coarse aggregates. These aggregates were used in the production of 30, 40, 50, and 60 MPa concrete to examine the effects at each grade. The study reports that due to the rough surface texture of the RCA compared to the natural aggregates, the slumps of the fresh concrete mixes were lowered by up to 78% which was attributed to increased inter-particle friction. For the compressive strength of the RCA concrete mixes, the rough surface texture had a positive effect as the mortar-aggregate bond was strengthened. For the 30, 40, and 50 MPa grades, the higher quality RCA of the three sources had the best compressive strength performance with up to 22% increase compared to the NA. In the higher strength 60 MPa mixes, the high-quality RCA still had up to 12% higher compressive strength compared to NA. Although the NA used in the study had higher strength than the RCA particles, this was not fully utilized with more failure planes occurring around the aggregate. The splitting tensile strength was also observed at each compressive strength grade but the differences between conventional and RCA concrete were found to be insignificant. It was determined that the properties of RCA concrete are most significantly influenced by adhered mortar content, aggregate density and surface texture which would need to be tested when attempting to classify and utilize RCAs (Butler et al., 2014).

The amount of adhered mortar on the surface of RCA is one of the most important factors influencing the properties of the new concrete produced. In the “Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars” this relationship between adhered mortar content and concrete mechanical and durability properties was analyzed (Duan and Poon, 2014). RCA obtained from three different sources was used in the production of concrete with compressive strengths ranging from 30 to 80 MPa utilizing 100% coarse aggregate replacement. It was observed that the density of concrete produced with RCA was lower compared to NA. It is stated that when using RCA with lower amount of adhered mortar (and correspondingly lower water absorption), it is possible to produce concrete with similar mechanical properties to NA concrete. The same observation was made for the durability properties of chloride ion penetration and drying shrinkage (Duan and Poon, 2014).

2.3.2 Pre-Treatment of RCA

Based on the literature studies presented, it can be seen that when using RCA in the production of new concrete, both the mechanical and durability properties of the material are impacted. These changes to the properties of the concrete are often controlled by using higher quality RCAs which have lower amounts of adhered mortar and with strengths which are comparable to natural aggregates. However, in many cases, the types of RCA available for a particular construction project can be limited to lower quality sources making their use more difficult. One way of overcoming this is by pre-treating the RCA used in order to improve their quality and performance. The study "Strength, shrinkage and creep and durability aspects of concrete including CO_2 treated recycled fine aggregate" examines one of the available treatment processes for RCA (Chinzorigt et al. 2020). The study investigated 100% non-treated coarse RCA mixes with fine RCA treated with CO_2 at a replacement ranging from 0 to 50%. The CO_2 pre-treatment was performed on crushed fine aggregates which were cured with CO_2 to promote carbonation and increase the strength of adhered mortar. It was found that by pre-treating the fine RCA used, the compressive strength of the resulting RCA concrete could be increased by up to 15%. For dimensional stability and durability properties there was little to no improvement with CO_2 treatment of fine RCA (Chinzorigt et al., 2020).

The paper "Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: A review" discusses several more types of RCA pre-treatments and provides analysis on the effects (Ouyang et al. 2022). The methods discussed in this paper included adhered mortar removal, polymer impregnation, carbonation, bio-deposition and pozzolanic slurry immersion. Although improvements were observed in the mechanical properties of the concrete produced, the study reported that the relationship between RCA treatment and concrete quality was very complex and depended heavily on the quality of the parent concrete. It was found that for the improvement of compressive strength in the concrete the most effective methods were carbonation and bio-deposition. However, the bio-deposition and pozzolanic slurry immersion treatments were found to be better for flexural and splitting tensile strength (Ouyang et al. 2022).

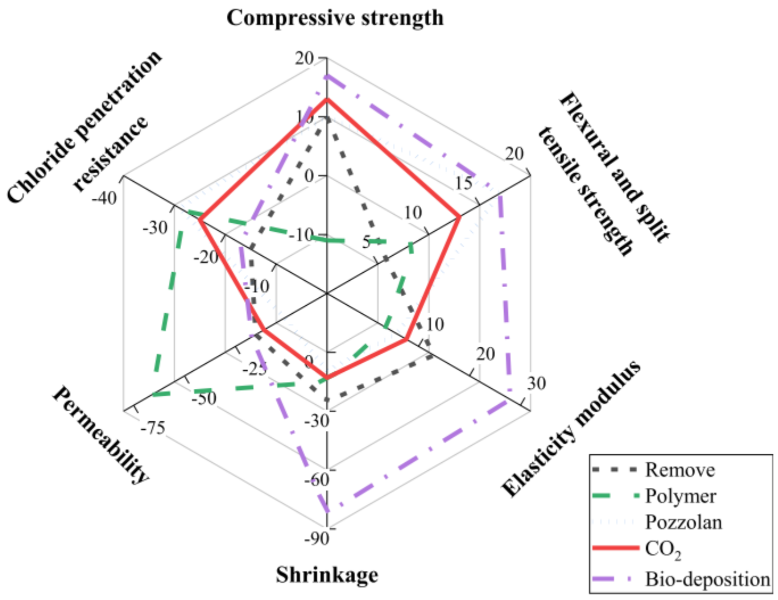
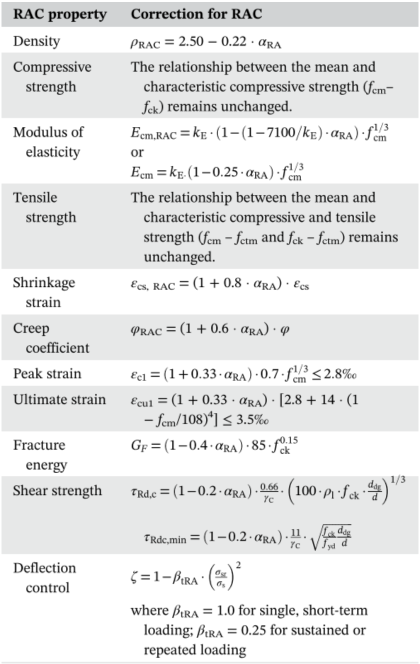


Figure 2-4: Effect (%) of different pre-treatment methods on the properties of RAC (Ouyang et al. 2022)

2.4 RCA Concrete Design Standards

Although RCAs have been used in concrete for several decades and research has been ongoing to better understand and improve the use of the material, they are still rarely utilized in the construction industry. Many studies have examined the mechanical and durability properties of concrete produced with 100% RCA but such high replacement ratios are extremely rare in real construction projects. One of the challenges for the adoption of RCA as a more common practice is the lack of codified design standards. It is known that with higher replacement ratios concrete produced with RCA will have inferior properties compared to conventional concrete and therefore, it requires special considerations during the design process. However, there are very few codified resources available to determine amendments to be made when using concrete with higher RCA replacement. The paper “Toward a codified design of recycled aggregate concrete structures: Background for the new fib Model Code 2020 and Eurocode 2” addresses this issue (Tosic 2020). Through an extensive literature review and analysis of results, the study proposes multiple adjustments to the *fib* Model Code 2020 and Eurocode 2 for the use of RCA concrete presented in Figure 2-5. In the paper, changes are proposed to the code for each relevant equation in terms of a α_{RA} value representing the combined replacement ratio of fine and coarse natural aggregates with RCA.



RAC property	Correction for RAC
Density	$\rho_{RAC} = 2.50 - 0.22 \cdot \alpha_{RA}$
Compressive strength	The relationship between the mean and characteristic compressive strength (f_{cm}–f_{ck}) remains unchanged.
Modulus of elasticity	$E_{cm,RAC} = k_E \cdot (1-(1-7100/k_E) \cdot \alpha_{RA}) \cdot f_{cm}^{1/3}$ or $E_{cm} = k_{E \cdot}(1-0.25 \cdot \alpha_{RA}) \cdot f_{cm}^{1/3}$
Tensile strength	The relationship between the mean and characteristic compressive and tensile strength ($f_{cm} - f_{ctm}$ and $f_{ck} - f_{ctm}$) remains unchanged.
Shrinkage strain	$\varepsilon_{cs,\ RAC} = (1 + 0.8 \cdot \alpha_{RA}) \cdot \varepsilon_{cs}$
Creep coefficient	$\varphi_{RAC} = (1 + 0.6 \cdot \alpha_{RA}) \cdot \varphi$
Peak strain	$\varepsilon_{c1} = (1 + 0.33 \cdot \alpha_{RA}) \cdot 0.7 \cdot f_{cm}^{1/3} \leq 2.8‰$
Ultimate strain	$\varepsilon_{cu1} = (1 + 0.33 \cdot \alpha_{RA}) \cdot [2.8 + 14 \cdot (1 - f_{cm}/108)^4] \leq 3.5‰$
Fracture energy	$G_F = (1 - 0.4 \cdot \alpha_{RA}) \cdot 85 \cdot f_{ck}^{0.15}$
Shear strength	$\tau_{Rd,c} = (1 - 0.2 \cdot \alpha_{RA}) \cdot \frac{0.66}{\gamma_C} \cdot \left(100 \cdot \rho_l \cdot f_{ck} \cdot \frac{d_{dg}}{d}\right)^{1/3}$ $\tau_{Rdc,min} = (1 - 0.2 \cdot \alpha_{RA}) \cdot \frac{11}{\gamma_C} \cdot \sqrt{\frac{f_{ck}}{f_{yd}} \frac{d_{dg}}{d}}$
Deflection control	$\zeta = 1 - \beta_{tRA} \cdot \left(\frac{\sigma_{sr}}{\sigma_s}\right)^2$ where $\beta_{tRA} = 1.0$ for single, short-term loading; $\beta_{tRA} = 0.25$ for sustained or repeated loading

Figure 2-5: Proposed Changes to fib Model Code 2020 (Tosic et al., 2020).

For the change in compressive strength between RCA concrete and NA concrete, the study presents what is found in the literature but does not provide an amendment to the codes as compressive strength value is specified in the design process. There is more importance placed on the variability of compressive strength for RCA concrete as this determines the material partial safety factor used in concrete design codes. However, from the literature reviewed in the study, it is found that the use of RCA does not have an effect on the variability of compressive strengths and there is no correlation with the aggregate replacement ratio (Tosic et al., 2020).

In north America, the American Concrete Institute specifies that the use of RCA concrete up to 100% replacement in structures is permissible as long as testing shows adequate mechanical and durability properties for the material produced (ACI., 2019).

2.5 RCA Concrete Structures - Case Studies

In addition to studies looking at the mechanical and durability properties of RCA concrete and proposing changes to design codes, case studies on the performance of real construction projects using RCA are also very important. These kinds of studies set precedent for the use of the material in the construction industry increasing the rate of adoption and also identify any challenges that can be faced when scaling up the use of RCA to an actual project. The paper “A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint” is one such study (Xiao et al. 2018). In this case researchers examine the construction of two identical high-rise structures, one built with RCA concrete and the other with NA concrete. Although the replacement ratio is kept limited at 30% of coarse aggregates and the foundation uses fully NA concrete, this is one of the few examples of significant RCA concrete use in a high-rise building. With the 30% replacement ratio of RCA concrete, the compressive strength is kept the same as the NA concrete with strength variability and deflection properties within the limits provided by the relevant Chinese design codes. With field testing, the static and dynamic characteristics of the two structures are found to be comparable (Xiao et al., 2018).

Another case documented in the literature was the Samwoh Eco-Green Building constructed with 100% RCA concrete in Singapore (Ho et al. 2015). The structure assessed in this study was a three-storey commercial building and the evaluation was performed following an analysis of the concrete mechanical properties. It was observed that with the materials used in this case the compressive, flexural, and splitting tensile strength were comparable to the NA concrete and this was achieved without changes to the water to cement ratio. Additionally, monitoring of the building following its construction in 2009 has revealed that deformation has stabilized and no issues were observed with any structural elements (Ho et al. 2015).

2.6 Life Cycle Assessment and ECO$_2$ Background

Research on the mechanical and durability properties of RCA concrete often shows comparable results to conventional NA concrete. Construction design codes and standards are gradually adopting the use of RCAs and many new construction projects are beginning to use the new material. The use of recycled construction and demolition waste in the production of new concrete helps reduce both the amount of waste generated and also the impacts of transportation associated with transporting natural aggregates great distances. With the rising scarcity of natural aggregates it is becoming more and more important that the effectiveness of RCAs in reducing environmental impacts is better understood. Although one can appreciate the qualitative environmental benefits of RCA concrete, it is necessary to have a quantitative assessment of such benefits to have the best approach to sustainable development.

2.6.1 Emergence of LCA

In the 1960s, concerns over the limitations of both raw material and energy resources created the need for a system to account for the consumption of resources. At the World Energy Conference in 1963, Harold Smith was one of the first researches to publish the calculations for energy requirements of several chemical products. In the following decades more studies on the consumption of non-renewable resources and the effects of changing populations on their availability highlighted the significance of the issue. More effort was put into the development of detailed calculations to understand the energy use and outputs of several industrial processes to better understand the depletion of fossil fuels and climate change. The foundations of current Life-cycle Inventory Assessment (LCIA) methods were first developed during an internal study by the Coca-Cola company for the comparison of environmental emissions and resource consumption of different container designs. Over the following years the methodology of Life-Cycle Assessment (LCA) was adopted by several companies for the purpose of similar comparative studies. With the contributions of governing bodies and organizations such as the EPA, the process evolved and improved over time (EPA, 2008).

2.6.2 LCA Process

LCA refers the processes used in the evaluation of “cradle-to-grave” industrial systems. In a “cradle-to-grave” system, the life cycle of a product is considered to begin at the extraction of raw materials and ends when the constituents have been returned through processes such as landfilling. LCA attempts to produce an accurate estimate of the environmental impacts of a product considering each stage of the product’s lifecycle. Using the results of an LCA, industrial products and processes and their impacts can be better understood, and environmental trade-offs can be highlighted. The LCA process can be described by the four main phases of Goal Definition and

Scoping, Inventory Analysis, Impact Assessment, and Interpretation which are presented in Figure 2-6.

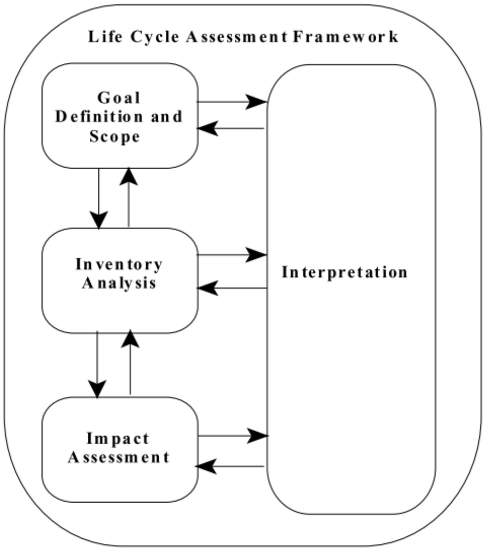


Figure 2-6: LCA Framework (EPA, 2008)

Goal Definition and Scoping is the first step of an LCA and involves the identification of the product or process being evaluated. During this first stage, the context of the assessment is identified along with the boundaries and scope of the analysis work and the environmental impacts to that will be the focus of the process. In the second stage of Inventory Analysis, each input and output of the process is identified and quantified. An example of an input could be the energy used in the process and outputs can include environmental emissions such as air and water pollutants. The Impact Assessment phase is when the results of the inventory analysis are used to judge the ecological and human impacts of the resources consumed as well as the emissions produced. The final phase involves the interpretation of the results of both the inventory and impacts analysis considering any uncertainties and assumptions made along the way to inform decisions (EPA, 2008). Companies often publish Environmental Product Declarations which are cradle-to-gate impact assessments of products such as Portland cement which were utilized in this study.

2.6.3 Equivalent Carbon Dioxide

During the Impact Assessment phase of a typical LCA, one of the tasks that need to be completed is the impact characterization. In impact characterization, a quantitative measure of human and ecological impact is produced by converting the results of the inventory analysis using science-based characterization factors. Using the new results, each life-cycle inventory considered in the study can be compared with respect to multiple impact categories such as acidification and ozone depletion. If the aim of the study is to determine the global warming potential of the activity, the inventory data concerning the release of greenhouse gasses such as methane and nitrous oxide during the process would be used. The characterization factor would be a separate value for each chemical representing the amount of carbon dioxide (CO_2) gas that would have the same impact on global warming as a single unit of the corresponding chemical. By multiplying the amount of greenhouse gases released provided by the inventory data with these characterization factors, the carbon dioxide equivalent of the process could be obtained. This new “equivalent” CO_2 value is helpful in comparing the global warming impacts of different processes without having to check each greenhouse gas emission separately (EPA, 2008).

2.7 Concrete CO_2 Emissions

One of the studies reviewed for insight into the use of lifecycle analysis in concrete was conducted by Flower DJM, Sanjayan JG in 2007 with the purpose of quantifying CO_2 emissions from the industry. The researchers stated that due to the lack of data in the field of concrete production footprint, designers had to base the emission values on estimates. The paper used data from multiple aggregate quarries and batching plant to generate new emission values for the concrete production and placement process. Flower and Sanjayan also reported that most of the emissions come from the production of cement with coarse aggregates responsible for 13 to 20%. The study found that the production of fine aggregates contributed only 30 to 40% of the emissions produced during coarse aggregate production since their production only required the grading of the material. Although admixtures were used in the production of concrete, the contribution to the total CO_2 emissions was found to be negligible. The emission impact of concrete batching and placing was also found to be very small compared to the other activities. In this study, the contribution of transportation was found to be very small in both the sourcing of aggregates and concrete delivery; however, as the distances between the corresponding facilities were not provided, the impacts could not be fully characterized (Flower and Sanjayan, 2007).

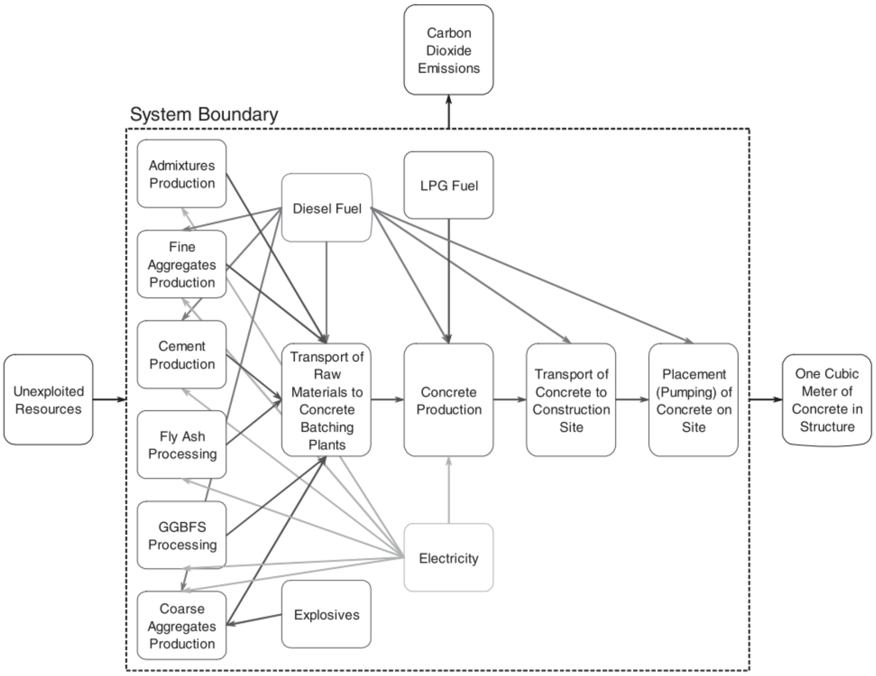


Figure 2-7: Concrete CO2 emissions system diagram (Flower and Sanjayan, 2007)

Another study which has assessed the carbon emissions of concrete was “The carbon footprint of reinforced concrete” which discussed mainly the emissions of reinforced concrete (Purnell 2013). The paper documented the carbon emissions of concrete production in terms of raw eCO_2 per unit mass of material and also eCO_2 per unit of structural performance. The eCO_2 per mass of material is observed to vary between 0.07 to 0.57 and depends heavily on the concrete strength, reinforcement and structure. It is stated that when considering eCO_2 per unit of structural performance, 50MPa concrete has a clear advantage.

2.8 Life-Cycle Assessment of Concrete Structures

When considering the design of new construction projects, there are some important trade-offs that need to be accounted for with respect to the interaction between material strength, dimensions and environmental impact. Material such as structural steel and high strength concretes can lead to a reduction in the dimensions of structural elements due to their superior mechanical properties however, they also require more resources and generate more emissions per unit volume. Lower strength materials can be produced at a cheaper cost and more sustainably but can lead to an increase in the dimensions (and resulting volume of concrete) of structural elements. Therefore, balancing the design, cost and environmental impact of a structure can be a challenging process which varies with the requirements of each unique construction project. Although lower strength concrete materials can have a reduced environmental impact of production (due the associated reduction in cement per cubic metre), for developments with higher mechanical performance demands, they can still lead to an overall increase in both costs and eCO_2 emissions. The paper "The carbon footprint of normal and high-strength concrete used in low-rise and high-rise buildings" presents a case study of this material optimization process (Fantilli et al. 2019). The study examined normal and high strength concrete mixes ranging from 25 to 80 MPa compressive strength in the design of three existing buildings with 14, 30, and 60 floors with design requirements prescribed by Eurocode 2. For the low-rise 14-storey structure, the 25 MPa concrete mix provided the lowest emissions at approximately 1625 tons of eCO_2 compared to the higher strength 60 and 80 MPa mixes which resulted in eCO_2 emissions of more than 1875 tons. The performance of the lower strength concrete was worse for the taller structures with approximately 16 000 tons of eCO_2 generated by 25 MPa concrete for the 60-storey building compared to 11 000 tons generated by the 80 MPa mix (Fantilli et al., 2019).

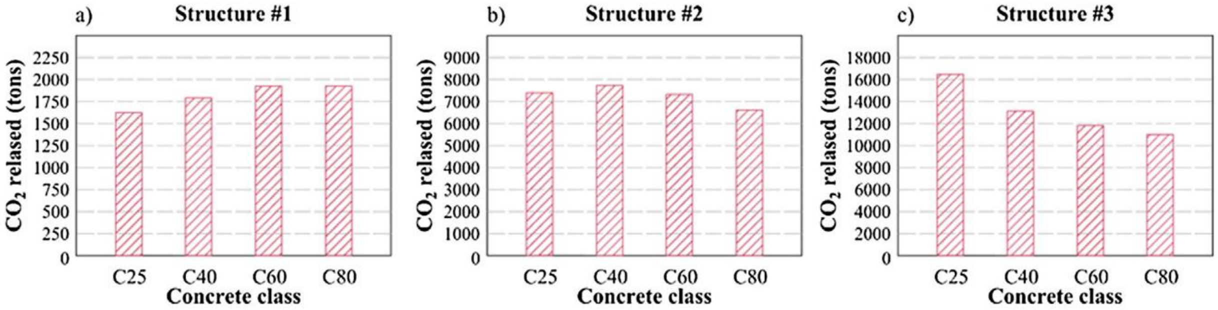


Figure 2-8: Carbon footprint of steel and concrete versus concrete strength for buildings with 14, 30, and 60 floors (Fantilli et al., 2019)

2.9 RCA Concrete CO_2 Emissions

To understand the sustainability benefits of RCA concrete, the same kind of LCA process used for natural aggregates needs to be completed in order to make comparisons possible. Jimenez (year) investigated how the LCA process can be used to assess the environmental impact of RCA concrete. In this study, a total of 10 different concrete mixes were studied with water-cement ratios of 0.5 and 0.7 and the replacement of coarse RCA ranging from 0 to 100%. For each concrete mixture, both the compressive strength and the eCO_2 emissions by weight were presented. For concrete mixes using a water-cement ratio of 0.5, the compressive strength for 0% coarse RCA was 32.5 MPa and gradually decreased with the addition of RCA to 29.8 MPa at 100% coarse RCA replacement. For a water-cement ratio of 0.7, compressive strength for concrete mixtures with 0% RCA was at 23.7 MPa and decreased to 19 MPa when 100% coarse RCA was used. With the use of RCA they also reported a very slight reduction in the carbon emissions with a 3.3 kilogram reduction in CO_2 between 0 and 100% RCA replacement for both strength grades. They concluded that the change in aggregate material did not result in a significant reduction in emissions as most of the CO_2 was produced by the use of cement at 218 to 305 kilogram of equivalent CO_2 for each concrete mix. However, the study did not consider the emissions resulting from the transportation of aggregates from the source making the values obtained only useful for the comparison of production-related emissions (Jimenez et al., 2018).

Another study which examined the emissions of RCA concrete compared to NA is “A closed-loop life cycle assessment of recycled aggregate concrete utilization in China” (Ding et al., 2016). In this study, a comprehensive LCA was performed which considered the emissions from manufacturing, transportation of material to site, and landfilling at the end of service life. The study placed a strong focus on the transportation of aggregates between quarries, demolition sites, recycling and batching plants due to the practices of the concrete industry in China. They found that due to the absence of limestone quarries near urban areas, trucks were often used to transport natural aggregates large distances. The study used data provided by industry surveys to set the distance of NA transport at 100 km while the more localized recycling process of RCA only required it to be transported a distance of 25 km. The concrete produced for the study consisted of three different mixes with a replacement ration of RCA at 0, 50, and 100% and used a water-cement ratio of 0.5. Due to the reduced mechanical properties often associated with RCA concrete, the researchers decided to increase the cement content used for each mixture depending on the RCA replacement ratio in order to counteract any reduction in compressive strength. This resulted in the use of up to 25 kilograms of additional cement for the 100% RCA concrete mix. The results showed that none of the mixtures were able to achieve a reduction in the emissions of equivalent CO_2 compared to the natural aggregate concrete with up to 0.76% higher emissions for 100% RCA use. The lack of improvement in sustainability in this case was attributed to the required increased use of cement in the RCA concrete mixtures. The study concluded that there was still potential for the reduction of emissions due to the difference in reduced transportation requirements between NA and RCA concrete (Ding et al., 2016).

Other countries where the use of RCA is being explored include India where the building codes regarding the production of concrete differ. In the 2009 study undertaken by researchers at the Indian Institute of Technology Kharagpur, the lifecycle analysis of RCA concrete mixtures were compared to conventional concrete considering multiple proportioning methods. The study examined concrete mixtures containing either 100% natural or RCA produced using conventional Indian Standards or the particle packing method for a total of four mixtures. Using the Ecoinvent 3.01 database along with data obtained from multiple production facilities, the researchers produced a lifecycle inventory for each case and quantified the environmental impacts through values such as the abiotic depletion and global warming potential. For each of the impact categories analyzed in the study, the production of cement had the largest contribution excluding Abiotic Depletion with transportation coming second. The concrete produced using natural aggregates and the conventional mix design method was observed to have the largest impact in each of the categories. The researchers also performed a sensitivity analysis of varying transportation distances for the aggregates as a fixed transportation scenario would limit the application of the study. As expected, the gap between the impact of natural aggregate and RCA concrete mixtures decreased as the demolition site became further from the recycling location. They concluded by highlighting that the reduced environmental impact achieved using RCA was attributed to the processing of the materials (Pradhan et al., 2009).

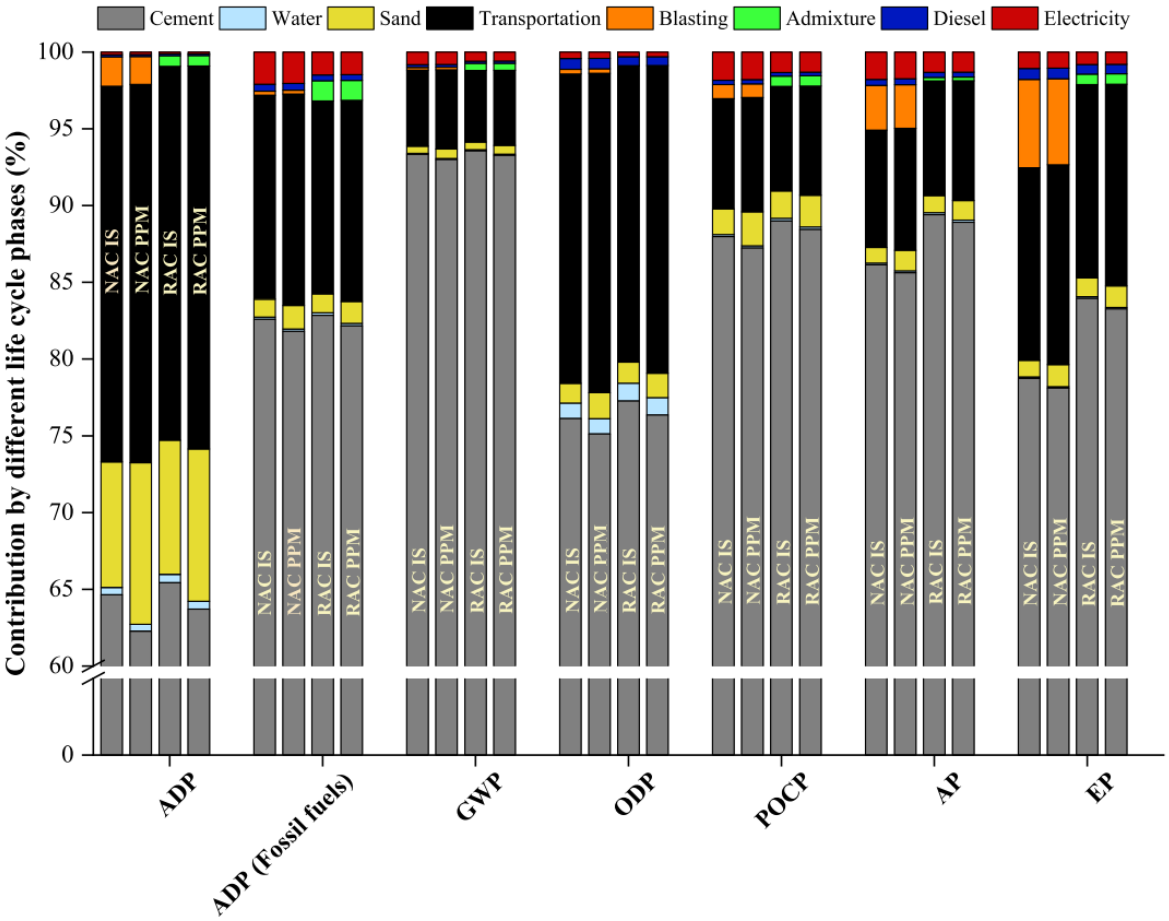


Figure 2-9: Contribution by different life cycle phases to different impact categories (Pradhan et al., 2009)

2.10 Lifecycle Assessment of RCA Concrete Structures

Although the mechanical properties and environmental impact of RCA concrete has been explored in many studies involving experimental work and emission research, the presence of larger scale case studies can be very helpful in the adoption of these materials. As the use of RCAs for structural applications such a high-rise construction is rare in North America, it is useful to observe work taking place globally to gain a better understanding of the material. In a 2018 study, researchers at Tongji University in Shanghai compared the sustainability of RCA concrete to conventional concrete in the construction of two identical 12-storey concrete buildings. This was done through a case study of a twin tower high-rise building where one tower used concrete produced with coarse natural aggregates while the other used an RCA concrete mixture which utilized up to 30% coarse RCA as a replacement for natural aggregates. Both towers were evaluated in terms of the concrete material properties and a lifecycle assessment was conducted to quantify the global warming potential of each tower separately. The study demonstrated that the use of RCA in concrete production did not significantly impact the mechanical properties and resulted in a smaller carbon footprint for the tower. The researchers observed that the main advantage of RCA concrete with respect to sustainability, was the availability of the material within the relative vicinity of the construction site compared to the quarried aggregates which had to be shipped large distances (Xiao et al., 2018).

2.11 Use of BIM with Lifecycle Assessment

With the rate of concrete consumption in the construction industry increasing with time, it is important that methods be developed for the reduction of environmental emissions in concrete production and use. Studies reviewed in this chapter have discussed several strategies such as the use of supplementary or recycled materials and how lifecycle assessments can be performed to better understand and improve carbon emissions. With the rising popularity of Building Information Modeling (BIM) and Digital Twin technology, the optimization of structural designs using an automated approach becomes possible. One study that presented how this could be achieved was “Investigating relationships between cost and CO_2 emissions in reinforced concrete structures using a BIM-based design optimisation approach” (Eleftheriadis et al. 2018). The researchers developed an integrated design approach which could optimise cost and carbon emission values of reinforced concrete structures through design decisions.

2.12 Summary and Identification of Research Gaps

Due to the growth of urban regions around the world, there has been growing concerns with respect to the availability of natural aggregate resources. Starting from 1997 with Baccini, there has been multiple studies undertaken by both governmental bodies and academic researchers on this potential issue. From the studies discussed, it can be seen that high quality natural aggregates used in the production of concrete are becoming increasingly scarce. Multiple regions are experiencing this problem with varying severity or will have difficulty sourcing aggregates in the future. With viable aggregate sources becoming increasingly further from urban centers where they are most needed, the associated aggregate shipping distances (and costs) will continue to increase. These increased hauling requirements for natural aggregates will result in both higher costs for construction and more negative environmental impacts.

Studies highlighting the issue of natural concrete aggregate scarcity often mention the use of RCA as a part of the solution. As a material used following the events of World War II to help in the reconstruction of European cities, this material can potentially be a significant source for aggregates in concrete production. Ongoing research has identified that with the use of RCA in larger quantities, concrete of comparable mechanical properties to NA can be obtained. Due to different sources of RCA with varying qualities, properties such as compressive strength can be reduced. Studies have shown that these properties can be further improved with the addition of extra binder material and also the pre-treatment of RCA particles. Amendments have also been proposed for design codes and standards which account for the changes in all properties of the material based on the growing body of research.

As the use of RCA in concrete with higher replacement ratios becomes more feasible, it is also critical that the sustainability effects are better understood. With the inferior strength of concrete often produced when using RCA, the increase in the volume of materials required can effect how sustainable the construction projects is. Although properties can be improved with pre-treatments or additional cement content, both off these options can cause significant increases in manufacturing emissions. Depending on projects specific requirement such as number of storeys and the distances to natural and RCA sources, the material which performs the best can also change on a case by case basis. Often when comparing these kinds of products, LCAs are performed in order to understand benefits and downsides of each option. From the studies reviewed, examples of LCAs done on both RCA and NA concrete mixes can be seen. Often the equivalent CO_2 value has been used to compare both recycled and natural aggregate concrete mixes with different strength grades and RCA replacement ratios. Studies have also performed LCAs on structures constructed with both RCA and NA concrete rather than just the material by unit weight. Although this type of research is less common, it is important in understanding the benefits of RCA as purely material based LCAs do not present a complete picture.

There are very few studies that have examined the effects of using reduced concrete compressive strength on the overall CO_2 emissions of a construction project. Often, the reduced mechanical performance of RCA concrete is remedied through the addition of extra cement which increases the emissions to beyond those of NA concrete as cement is the main contributor to global warming potential. Although the reduced compressive strength (associated with using RCA concrete) might result in larger structural element dimensions and increased concrete requirements, emissions reductions may still be realized due to RCA concrete's lower equivalent CO_2 per unit volume compared with conventional concrete. The effects of material transportation requirements on the emissions generated during construction are also rarely documented. From the literature reviewed, the hauling distances for natural aggregates vary significantly with the availability of quarries while RCA is assumed to be more locally available. Studies often use distances common to a chosen site in the region; however, examining varying distances for the two materials can help make recommendations depending on different scenarios.

Overall List of Research Gaps:

- Evaluating RCA concrete in structural design with no additional cement content
- Examining effect of varying transportation requirements on RCA sustainability and cost
- Evaluation of reinforced concrete design process with RCA concrete

CHAPTER 3: Research Methodology

3.1 Overview

In this chapter, the methodology for this thesis will be discussed in further detail with the steps taken to achieve the main objectives of the research work. The first two steps taken were the design of a simple reinforced concrete structure along with a consistent process of altering the design as required and the construction of a database of natural and RCA concrete compressive strengths and eCO2 emissions. Following these preliminary steps, multiple analysis scenarios were generated depending on the quality (compressive strength) of material used, floor slab design, where RCA was utilized, and transportation requirements. For each scenario, material use, eCO2 emissions, and construction costs were calculated and compared. It was decided that this type of study is valuable as the interactions of RCA concrete use and reinforced concrete design and the resulting effects on sustainability and financial impact have not yet been comprehensively documented. The chapter will present details of the steps of eCO2 calculation, cost estimation, and structural design. Figure 3-1 presents the general flow of research work leading to the generation and analysis of each scenario considered. First, the compressive strengths were obtained for the concrete that was used from the database of mixes which will be discussed further in Chapter 5. Using the material compressive strength and the site specific design influences such as wind loads, each structure was designed following the same process which is detailed in Chapter 4. For each structure, the volumes of material required were calculated. For the “Lifecycle Analysis of Materials” portion of the process, eCO_2 emissions were calculated per unit of material (concrete/steel) used which is discussed in the next sub-section. Finally, knowing the volume of materials used, the unit cost and the unit eCO_2, the total carbon emissions and cost of each structure was calculated. This figure presents the overall process that was followed for each hypothetical structure analysed in the scenarios.

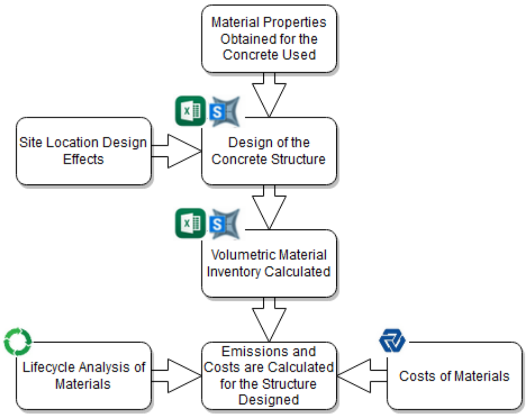


Figure 3-1: Process Flow Diagram

3.2 Equivalent CO_2 Emissions Literature Analysis

To estimate the carbon footprint of a unit volume of concrete, this research used emission statistics for the concrete constituent materials obtained from multiple research studies in the literature. Equivalent CO_2 emissions values for materials such as reinforcing steel, ordinary Portland cement, and coarse and fine natural aggregates were obtained from both academic studies and Environmental Product Declarations (EPD) published by construction material companies such as Icdas and Capitol Aggregates. Statistics on the emissions generated by the transportation of aggregates by truck were also obtained through publications by the EPA, the City of Winnipeg, and assessments completed in China. A procedure was created using these values to calculate eCO_2 emissions for a given set of concrete mixture proportions and an aggregate transportation scenario. All emission values were grouped into different categories such as aggregate production, cement production, and transportation by road and an average value was used for each category. When examining a concrete mixture, for each constituent, the weight of material used per unit volume of concrete was multiplied by the emissions produced during the manufacturing of a unit weight of the material. As this constituent also needs to be transported to the construction site, the weight of the material used is multiplied by the transportation emissions caused by the transport of a unit weight and distance which is added to the total eCO_2 value as described in Equation 3-1.

$$\begin{aligned} Concrete\ eCO_2 = & \sum (Weight \times eCO_2\ per\ kg)_{Constituent} \\ & + \sum (Weight \times Distance \times eCO_2\ per\ ton \cdot km)_{Transportation\ Instance} \\ & + eCO_2\ Batching \end{aligned} \tag{3-1}$$

The emission values used as part of this study were extracted from the publications of several industry and government organizations which are presented in Table 3-2. The reports on emission values were chosen for review based on the availability of the data, credibility of the EPD backed by the relevant organizations, and the requirements of the project such as eCO_2 reporting without transportation impacts.

Table 3-2: Additional Data Sources Used for LCA

Industry Sources	Information Obtained
Capitol Aggregates Inc 2015	Cement emissions
City of Winnipeg 2012	Transportation emissions
Commercial Metals Company 2016	Reinforcing steel emissions
Concrete Reinforcing Steel Institute. 2017	Reinforcing steel emissions
Icdas 2015	Reinforcing steel emissions
Kangley Rock & Recycling 2018	Recycled aggregate emissions
Martin Marietta Aggregates 2017	Natural aggregate emissions
Polaris Materials 2017	Natural aggregate emissions
Portland Cement Association 2016	Cement emissions
Sherwood Steel LTD. 2017	Reinforcing steel emissions
Vulcan Materials. 2016	Natural coarse aggregate emissions

3.3 Structural Design and eCO_2 Evaluation

Using the maximum, median and minimum strength reduction values determined based on the literature analysis, three levels of concrete "quality" (low, median, and high) were established for the RCA concrete mixes to be used in this research. "Quality" in this context, corresponds to the reduction in compressive strength relative to an equivalent conventional concrete mixture (i.e., the strength reduction ratio). The high-quality RCA concrete mixtures corresponded to either a net increase or no change in compressive strength relative to the control concrete. In cases where an increase was noted, a minimum strength reduction ratio of 0% was assumed, thus the compressive strength values used for the design the same as the equivalent concrete mixtures (i.e., 30 and 50 MPa). The median-quality RCA concrete used compressive strength values of 25 and 45 MPa while the high-quality RCA concrete used compressive strengths values of 20 and 30 MPa. The first step after the appropriate RCA concrete compressive strength values were determined for the concrete was to complete a two-way (punching) shear check. If the shear resistance of the floor slab was found to be satisfactory, the design process continued and utilized SAP2000 where the column reinforcement quantities were computed. If the shear capacity of the floor slab was found to be inadequate, either the column dimensions or the depth of the slab were increased. As the majority of the volume of concrete used in the building was attributed to the floor slabs, the width of the columns were increased before the slab thickness was modified. Once the dimensions of the columns and floor slabs were established, the required flexural steel reinforcement in the slab was computed. Using built-in design tools provided by SAP2000 (which followed the design provisions of CSA A23.3-14), once the design was finalized, the volumetric quantities of the total amount of concrete and reinforcing steel was automatically generated. This inventory provided the separated volumes of concrete and steel used in the construction of each group of elements including the columns, slabs, and walls.

3.4 Cost Analysis

The estimation for the cost of concrete was done through the use of RSMeans data for 2021 (RSMeans 2021). In a process similar to the calculation of eCO_2, the cost of each constituent used in the production of the concrete was taken from the RSMeans concrete materials database (RSMeans 2021). In addition to the cost of materials, the price of labour was also considered which depended heavily on the design of the structure. During the structural design process, all required values such as the surface area of concrete used for the calculation of forming costs needed to be computed. Using the recorded information of the design as well as the unit cost of materials and labour, a cost could be calculated for the entire structure for each of the design scenarios.

CHAPTER 4: Description of Hypothetical Structure and Design Approach

4.1 Overview

The structure designed as part of this research was a 21-storey reinforced concrete office building. This type of structure was selected as a case study as it was assumed to represent a standard form of building in a major urban or suburban setting. Choosing a standard building on which to base the analysis and findings from this study will presumably ensure that the conclusions produced will be more widely applicable to other typical reinforced concrete buildings. Although data on the average number of floors found in such structures is scarce, the number of storeys considered in this project was based on a previous hypothetical structure study considering similar buildings (Fantilli et al., 2019).

4.2 Geometric Layout and Structural Loading Assumptions

Both a flat plate and flat slab floor system designs were considered to analyze the effect that each floor system type has on the total eCO_2 emissions of the structure. The reinforced concrete frame consists of 25 square bays with conventional shear (core) walls which were designed to resist lateral forces (i.e., wind and earthquake) in each orthogonal direction. The structure consists of a ground floor storey height of four meters and continues with a height of three meters on all other floors. Each bay spans six meters in each direction between the supporting square columns. The number of storeys, number of bays, storey heights, and bay dimensions are kept consistent for all design scenarios. The designs for the floor slabs, column dimensions and shear walls were completed through spreadsheet-based calculations, while the columns reinforcement quantities were determined using built-in reinforced concrete design features in SAP2000 (which followed the design provisions of CSA A23.3-14). Figure 4-1 presents the overall design of the structure with the SAP2000 model used during the structural analysis and design, while Figure 4-2 presents the floor plan.

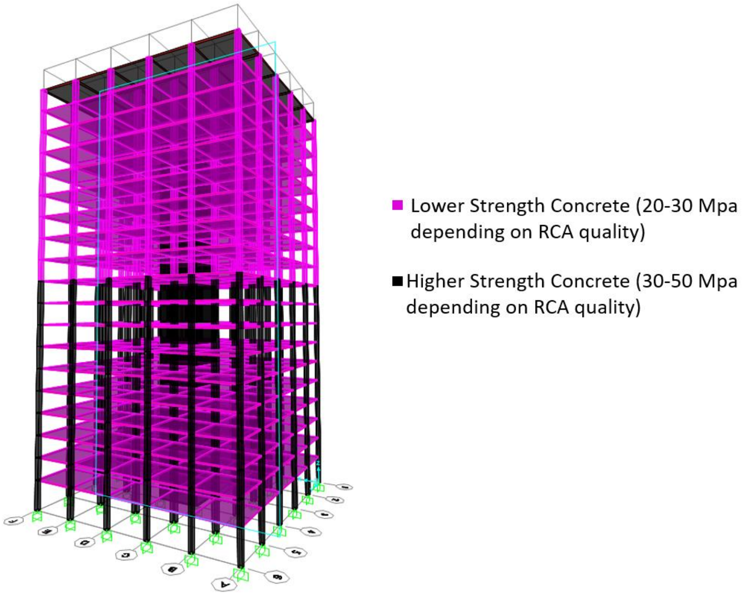


Figure 4-1: Structure Frame Model

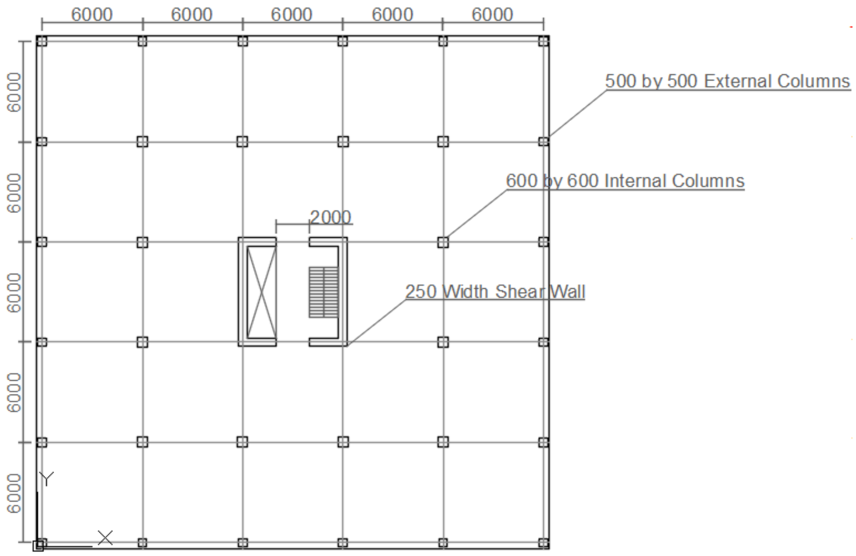


Figure 4-2: Structure Floor Plan

The design of the building was completed in accordance with the National Building Code of Canada (NBCC 2015). As the structure is an office building, the appropriate live (3.6 kPa) and dead (1.5 kPa) gravity loads were applied to the floor system for design calculations. As the final floor of the structure was considered to be a mechanical penthouse, a live load of 7.2 kPa and a dead load 4.5 kPa were applied. For the roof of the structure, 1.5 kPa, 4.8 kPa, and 1.4 kPa were applied for the dead, live and snow (including rain) loading, respectively. For the purposes of calculating the associated snow, rain, wind, and earthquake loading, the case study building was assumed to be located in Toronto, Canada.

As the most concrete mix data found during the development of the database detailed in Chapter 5 was for the strength groups of 30-39 MPa and 50+ MPa, the decision was made to use 30 and 50 MPa concrete for the design of the control structure. The control structure represents the design of the building with no reductions in strength. As there are only two grades of concrete used with 30 and 50 MPa compressive strength in the initial control design, they are referred to as LSC and HSC respectively. The HSC was used in the construction of columns in the first 10 floors of the structure, the floor slab carrying mechanical gravity loads, and the core walls as presented in Figure 4-1. The LSC concrete was used in the remaining columns of the building, and all typical floor slabs (i.e., not including ground floor slab or mechanical penthouse floor).

4.3 Gravity Load Carrying System

The design of the gravity load carrying system began with the calculation of the initial slab thickness, h_s, in accordance with Clauses 13.2.3 and 13.2.4 from CSA A23.3-14. Equations 4-1 and 4-2 are used to calculate slab depth with respect to deflection requirements based on clear span length, steel reinforcement, and depth of drop panels.

$$h_s \leq \frac{l_n(0.6 + \frac{f_y}{1000})}{30} \tag{4-1}$$

$$h_s \leq \frac{l_n\left(0.6 + \frac{f_y}{1000}\right)}{30} - \frac{2x_d}{l_n}\Delta_h \tag{4-2}$$

Where:

$l_n = longer\ clear\ span$

$f_y = reinforcement\ strength$

$x_d = drop\ panel\ width$

Next, the slabs were checked for two-way (punching) shear at the square columns as specified by Clause 13.3.4.1 from CSA A23.3-14. This process was automated using a spreadsheet, in which the slab depth and column dimensions could be manually changed until the preliminary punching shear checks were satisfied. The shear perimeter and resistance were then computed for the interior, edge, and corner columns to check for punching using equations 4-3, 4-4, and 4-5,

$$V_r = V_c = \left(1 + \frac{2}{\beta_c}\right) 0.19\lambda\phi_c\sqrt{f_c'} \tag{4-3}$$

$$V_r = V_c = \left(\frac{\alpha_s d}{b_o} + 0.19\right)\lambda\phi_c\sqrt{f_c'} \tag{4-4}$$

$$V_r = V_c = 0.38\lambda\phi_c\sqrt{f_c'} \tag{4-5}$$

Where:

$V_r = factored\ shear\ stress\ resistance$

$\beta_c = ratio\ of\ long\ side\ to\ short\ side\ of\ reaction\ area$

$\alpha_s = 4\ for\ interior, 3\ for\ edge, and\ 2\ for\ corner\ columns$

$b_o = shear\ perimeter$

Next, the formulae in the spreadsheet calculate design moments over the whole floor system according to Clause 13.9.2.2 and 13.9.3 from CSA A23.3-14. The design moments calculated in equation 4-6 are distributed among the column and middle strips of the floor system.

$$M_o = \frac{w_f l_{2a} l_n^2}{8} \tag{4-6}$$

Table 4-1: Interior Span Moment Distribution (CSA A23.3-14)

Negative factored moment at the face of support	0.65
Positive factored moment at midspan	0.35

Table 4-2: End Span Moment Distribution (CSA A23.3-14)

Moment	Exterior edge unrestrained	Slab with beams between all supports	Slab without beams between interior supports	Exterior edge fully restrained
Interior negative factored	0.75	0.70	0.70	0.65
Positive factored	0.66	0.59	0.52	0.35
Exterior negative factored	0	0.16	0.26	0.65

The appropriate amount of flexural and integrity reinforcement was calculated as prescribed by Clause 13.10 in CSA A23.3-14 with the required curtailment lengths from Figure 4-3. Figure 4-4 highlights how the reinforcement was distributed among the design strips of a typical floor flat plate floor slab.

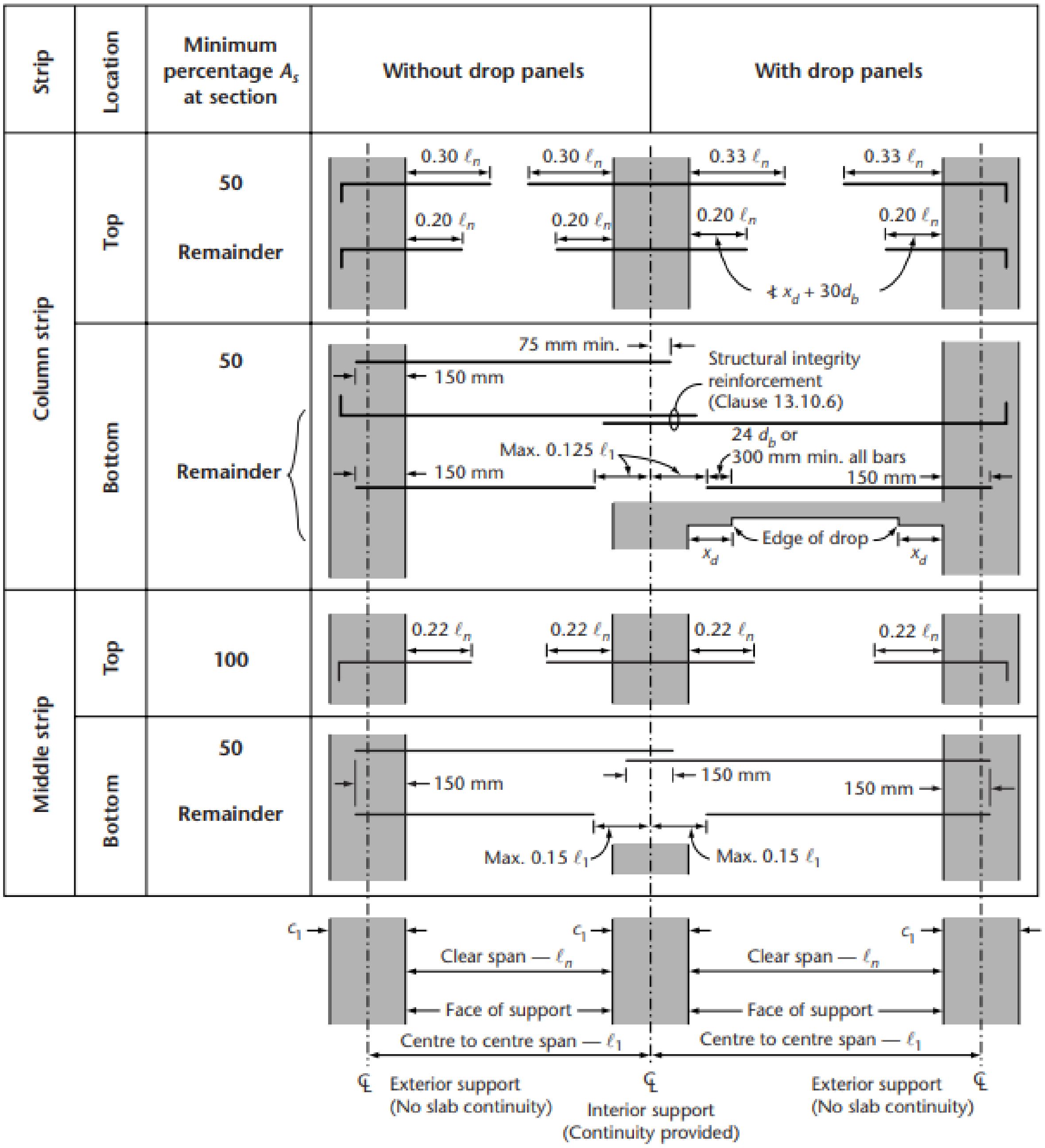


Figure 4-3: Curtailment of Slab Reinforcement (CSA A23.3-14)

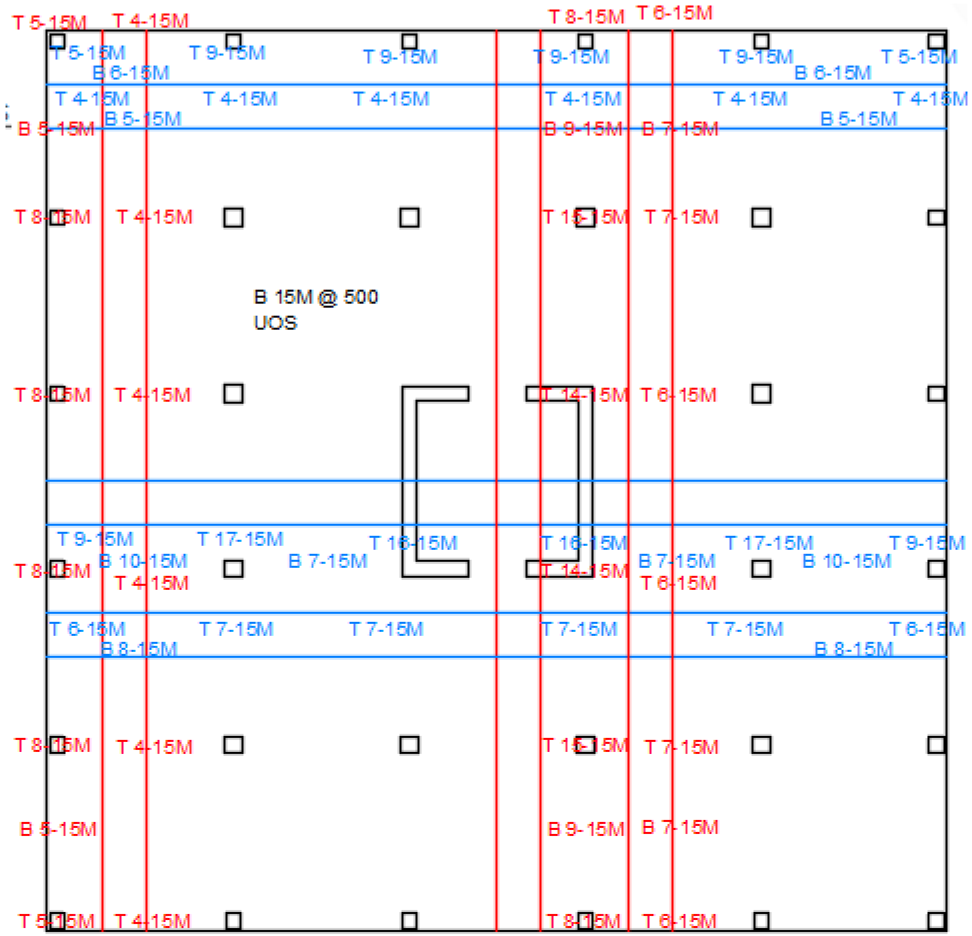


Figure 4-4: Typical Slab Top and Bottom Reinforcement by Design Strip (Red for N-S and Blue for E-W)

Once the slab design was completed, the design proceeds by computing the column reinforcing steel. Once again, the built-in reinforced concrete design features of SAP 2000 were used by producing a biaxial interaction diagram for each of the column elements in the model. Based on the required capacity, reinforcement ratios for each column in the structure were automatically generated. At this step, the SAP 2000 will not provide a reinforcement ratio for the column cross-section if the required reinforcement surpasses the maximum possible for the column (0.08 times gross area). In cases where this was found to occur, the floor slab design spreadsheet was revisited and the column dimensions were increased followed by re-input to SAP2000 for new reinforcement ratios. Finally, the column reinforcement was calculated using a spreadsheet to determine the final volume of reinforcing steel required.

Based on the design process outlined above, the flat plate control structure designed using the 30 and 50 MPa conventional concrete, the initial typical floor slab depth was determined to be 200 mm from preliminary shear checks. Due to the higher gravity loading in the mechanical penthouse, the corresponding reinforced concrete floor slab was designed with a depth of 275 mm. Throughout the height of the building, the exterior (perimeter) square columns were 500 mm in width while the interior columns were 600 mm.

4.4 Lateral Load Resisting System

The lateral load resisting system for the structure consisted of a set of reinforced concrete shear core walls. The design of the lateral load resisting core walls was completed using spreadsheet-based calculations and in accordance with CSA A23.3-14. In this study, the values for seismic and wind loads are based on the Greater Toronto Area data for events with a return period of 1-in-50 years. The seismically induced base shear value was computed using the equivalent static force procedure specified outlined in NBCC 2015 clause 4.1.8.11 and equation 4-7.

$$V = S(T_a)M_v I_E W/(R_D R_o) \tag{4-7}$$

Where:

$T_a = fundemental\ lateral\ period$

$M_v = higher\ mode\ factor$

$I_E = importance\ factor$

$W = weight\ of\ the\ building$

$R_D = ductility\, related\, force\, modification\, factor$

$R_o = overstrength\, related\, force\, modification\, factor$

Based on the dimensions and the weight of all of the elements, the period of the building is first calculated through equation 4-8 which is used to determine the shear and moment acting on the lateral load resisting system.

$$T_a = 0.05(h_n)^{3/4} \tag{4-8}$$

Where $h_n = building\ height$

Once the shear and moment from wind loads are also calculated, both values are compared and the worst case is used from the two scenarios. For the design of shear walls, following an assumption for the width with clause 14.1.7 in mind, minimum horizontal and vertical distributed reinforcement requirements were calculated as prescribed by clauses 14.1.8.6 and 7. The strength of the shear wall was then determined through Equation 4-9 (Cardenas and Magura, 1973).

$$M_r = 0.5\phi_s f_y A_{vt} l_w \left(1 + \frac{P_f}{\phi_s f_y A_{vt}}\right)\left(1 - \frac{c}{l_w}\right) \tag{4-9}$$

Where:

$A_{vt} = area\ of\ distributed\ vertical\, reinforcement$

$c = neutral\ axis\ depth$

The initial control structure core wall designed with 50 MPa compressive strength concrete was 250 mm in width with minimum 0.15% distributed reinforcement and 12-25M bars for concentrated reinforcement at each end. The horizontal reinforcement needed was also calculated at 0.20% minimum distributed to completely represent the steel requirements of the design.

The seismic load demand can vary significantly across Canada and therefore, the design, particularly of the shear wall system could change since the values used corresponded to Toronto. However, given that the total volume of concrete in the building is mainly attributed to the slabs and columns, variation in shear wall design would likely have negligible impact on total eCO_2 and construction costs.

4.5 Assumptions Regarding Foundation Design

For this study, the design of the foundation was not considered as it was assumed that in all design scenarios, the foundation would not utilize RCA concrete. The main reason for this was the increased mechanical and durability requirements for concrete used in this application. Considering that all scenarios considered would share the same design for the foundation, this step of the design process was also omitted. Although there was the possibility of increase structure weight due to design changes and therefore a requirement for different foundation designs, this was confirmed to be unnecessary after analysing the changes. With a column run-down comparison of the scenario structures, it was found that the change in weight was negligible.

4.6 Summary

In order to keep the analysis results between the different scenarios consistent, the same process for designing and altering the structure was used each time. The process which has been discussed in detail throughout this chapter is also presented visually in Figure 4-5. In addition to this chapter, sample spreadsheet calculations which were performed have been provided in Appendix A.2.

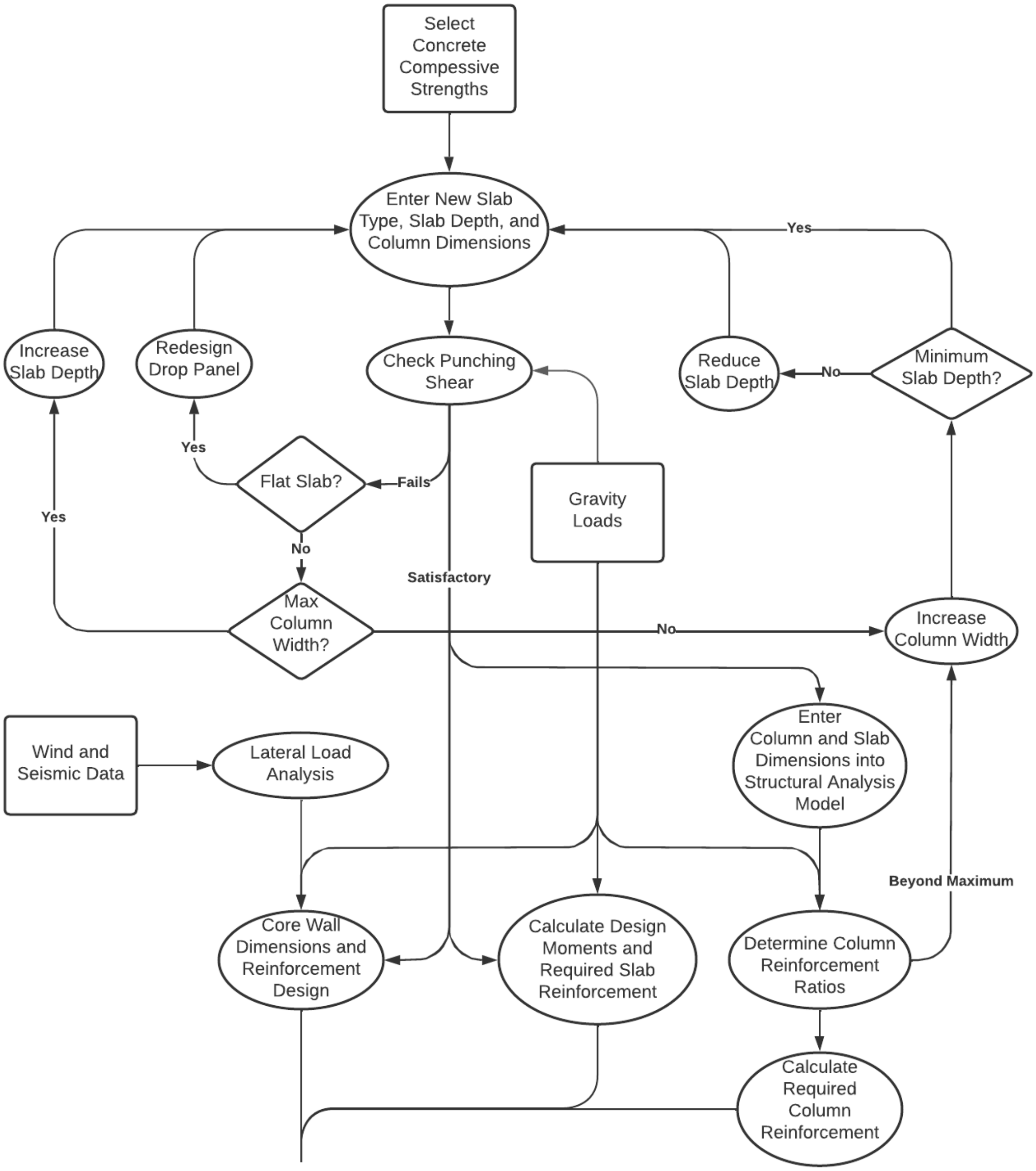


Figure 4-5: Integrated Structural Design Framework

CHAPTER 5: RCA Concrete Compressive Strength and Equivalent CO_2 Literature Database

5.1 Overview

In this chapter, the first stage findings of the desktop study will be discussed. As part of the first step in this research, an initial pilot study was designed and conducted which considered only three design scenarios. The objectives of the pilot study were twofold: first, to help better understand and develop the structural design and eCO_2 quantification process and, second, to produce some preliminary results on the effect that using RCA concrete has on the structural design of a typical reinforced concrete structure. Based on the observations from this pilot study, additional design scenarios were identified for incorporation in the main body of the research work. The pilot study also highlighted the need for better understanding of the variability of computed eCO_2 values, of different concrete mixture proportions, the compressive strength reductions due to RCA and justification for design strength choices. These findings from the pilot study subsequently led to the development and analysis of a literature database of RCA concrete mixtures which allowed for the quantification of compressive strength and eCO_2 variability.

5.2 Pilot Study

Building upon the structural design of the control structure presented in Chapter 4, the pilot study used the same structural design. Findings were published in a conference paper “Investigation of Design and Trade-Offs in Concrete Structures Using Recycled Materials for Reduction of Carbon Emissions” for the fib Symposium 2021.

5.2.1 Design Scenarios

Three design scenarios (Control, RCA-A and RCA-B) were considered and evaluated in the pilot study. The first scenario (Control) consisted of the design of the control structure using conventional concrete. Design Scenarios RCA-A and RCA-B consisted of the design of the structure using various RCA concrete mixture designs, produced with RCA sources of varying quality.

The mechanical properties of the RCA-A were taken from recent testing undertaken while developing new RCA concrete mixes for the masters thesis “Development And Structural Performance Assessment of Low-carbon Concrete Using Recycled Concrete Aggregates And Secondary Materials” (Santorsola 2021). While the RCA-B mixtures used within the analysis were based on the mechanical properties of previously tested mixtures developed under laboratory conditions which were presented by Butler et al. (2014). Both the RCA-A and B concrete mixtures (LSC and HSC) had 100% (by volume) of the natural coarse aggregates replaced with coarse recycled concrete aggregate (CRCA) and consisted of CRCA sources of varying quality. The purpose of using two pairs of mixtures with such a significant difference in RCA quality was to investigate the effect of material variability on RCA concrete compressive strength. Table 5-1 presents the mixture proportions and the fresh and hardened properties for the concrete mixes considered in the study.

Table 5-1. Mixture proportions and fresh and hardened material properties

Scenario	**Mix ID**	**Mix Proportions (kg/m^3)**					**Slump (mm)**	**Compressive strength Target (Measured) (MPa)**
		Cement	**Water**	**Coarse Natural Aggregate**	**Coarse Recycled Concrete Aggregate**	**Fine Natural Aggregate**		
Control	LSC-Control	305	201	1035	0	752	90	30 (34.2)
	HSC-Control	507	234	1035	0	505	105	50 (56.8)
RCA-A	LSC-RCA concrete	305	210	0	935	751	75	30 (28.8)
	HSC-RCA concrete	507	243	0	935	504	65	50 (33.4)
RCA-B	LSC-RCA concrete	267	160	0	975	863	25	30 (44.1)
	HSC-RCA concrete	474	180	0	975	635	35	50 (59.0)

Mixture proportions do not consider aggregate water absorption

*Refer to Butler, West, and Tighe 2014 (RCA-B) and Santorsola 2021 (RCA-A)

As shown in Table 5-1, it was found that the RCA-A concrete mixtures had 4-33% lower compressive strength values than the target compressive strength values for LSC and HSC (i.e., 30 MPa and 50 MPa). Compared with the RCA-B mixtures which consisted of CRCA sourced from decommissioned municipal infrastructure such as sidewalks; the CRCA sources for the RCA-

A concrete mixtures contained a significant portion of impurities such as crushed clay bricks. As a result, the lower quality of the RCA-A sources may have resulted in the reduced concrete compressive strengths for both RCA-A concrete, while the higher quality of the RCA-B source (did not contain deleterious substances), resulted in much higher compressive strengths of the RCA-B concrete.

Due to the lower strength of the RCA-A mixtures compared with the conventional concrete mixtures, the design of the structural elements used within the building model were revised to meet structural requirements by increasing member dimensions (with proportional increases in concrete volume) and by increasing reinforcement ratios resulting in additional reinforcing steel.

5.2.2 Equivalent CO_2 Emissions Assessment

Using the compiled LCA data along with the different building design scenarios, eCO_2 emissions were calculated for each scenario. Table 5-2 presents the total building eCO_2 emissions calculated per cubic meter of concrete used for each of the mixtures examined as well as the eCO_2 emissions for the steel reinforcement. In each of the design scenarios, the total volume of concrete and reinforcing steel required was recorded and, using the values reported in Table 5-2, the carbon footprint of the structure was calculated. Although the total building eCO_2 emissions is not the only environmental impact category considered during a full LCA, it can serve as an indicator of how effective the RCA concrete is in improving sustainability of the completed structure. Some categories such as abiotic depletion can show significantly better performance for the RCA concrete as the consumption of natural resources in large concrete volumes is further relied upon (Pradhan et al., 2019). While the scope of this research has been limited to quantifying the eCO_2, the exploration of all the various LCA impact categories with respect to the use of RCA concrete is an interesting direction for future research in this area.

Table 5-2. Equivalent CO_2 emissions per cubic meter of concrete for each mixture

Control (30 MPa)	**Control (50 MPa)**	**RAC A (30 MPa target)**	**RAC A (50 MPa target)**	**RAC B (30 MPa target)**	**RAC B (50 MPa target)**
378 kg/m^3	559 kg/m^3	310 kg/m^3	491 kg/m^3	278 kg/m^3	463 kg/m^3

5.2.3 Preliminary Results and Discussion

For each of the design scenarios, the materials used were grouped into: low-strength concrete (used for floor slabs), high-strength concrete (used for base columns and walls), and steel reinforcement. As expected, the largest volume of concrete was attributed to the construction of the slabs. After calculating the eCO_2 emissions for each of the design scenarios, a comparison was made with the control (conventional concrete) design. Figure 5-1 shows the total eCO_2 emissions generated for each of the design scenarios examined along with a summary of the contributions from each structural element type.

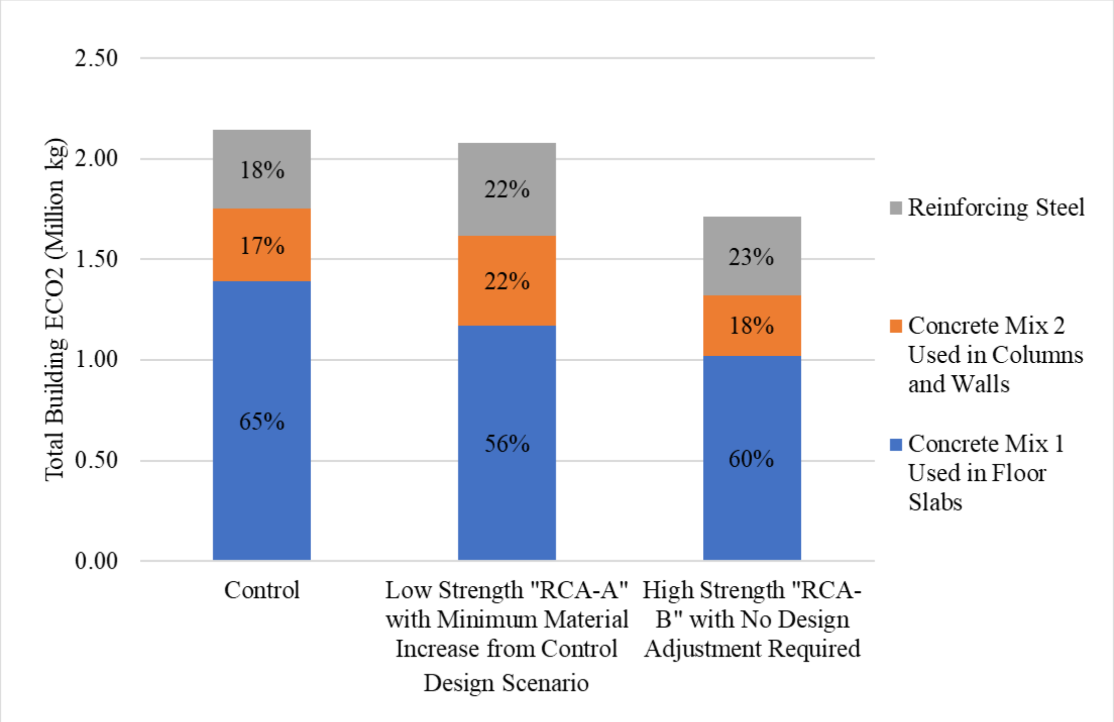


Figure 5-1. Carbon emissions for each building designed.

Based on this evaluation, the control structure which utilized conventional concrete resulted in the highest total building eCO_2 values which were 25% higher compared to the RCA-B mix. The control and RCA-A structures released 2.14 and 2.08 million kilograms of eCO_2 respectively, showing a slight improvement with a 3% decrease in eCO_2 from control. As expected, the high strength RCA-B concrete mix performed much better compared to both the control and low-quality RCA-A mixes. With no need to increase structural dimensions or steel reinforcement quantities due to the reduction of concrete strength, the environmental benefit of using higher quality RCA in concrete is demonstrated in this analysis. With no strength change between the conventional and RCA concrete mixes, the emissions were found to be as low as 1.71 million kilograms with the methods considered in this study. Although this level of performance may be rare with the construction and demolition waste (CDW) sources currently available, it was assumed that most RCA concrete mixtures would be of a similar quality as the two RCA sources considered in this pilot study. One trend visible in Figure 5-1 is the decrease in the contribution of the lower strength "LSC" used in the typical floor slabs of the structure with RCA concrete. The contribution of "HSC" used in the columns and shear walls similarly decreases with smaller member dimensions but increases with the use of RCA concrete.

One of the interesting considerations which arose during this pilot study LCA was the possibility of using RCA concrete selectively, in specific structural members throughout a building. As stated previously, the use of the RCA concrete seemed to increase the eCO_2 contribution of the higher strength mix used in the columns and walls while decreasing eCO_2 for the lower-strength mixes used in the slabs. Additionally, RCA concrete of higher compressive strength (i.e., 50 MPa), seemed to be less achievable (based on published literature) as compared to strengths of 30 MPa. Considering this finding, a potential hybrid design using RCA concrete for floor slabs and conventional concrete for the columns and shear wall elements was proposed as a future design scenario consideration in subsequent studies.

Although the focus of this pilot study was the global warming potential of the materials used in the structure, this is not the only approach available with an LCA. Other impact categories often analysed during an LCA can include abiotic and ozone layer depletion. In this study, the generation of eCO_2 was used as an indicator of material sustainability, but it will be important to also consider these other impact categories as part of future research.

When gathering the data presented in this pilot study, there were several assumptions made that need to be identified. One of the limitations of the current study was the constraints of the structural design imposed for the simplification of the process. All designs featured almost the same structure with a flat plate floor system. The exploration of alternate structural systems such as flat slabs making use of drop panels was identified as an alternate design scenario in subsequent research. Examining the design process used in this study, one of the disadvantages for the RCA concrete mixes was the reduction of shear strength in the slabs leading to punching failure at the columns. From preliminary analysis of similar designs using drop panels, it seems that the performance of the RCA concrete mixes can be significantly improved in this area.

During the gathering of LCA data used for the pilot study to quantify the global warming potential, several important assumptions were made that could have influenced the results. The emissions were recorded per unit mass of concrete constituents (i.e., for the cement powder and the natural aggregates). Often, the values extracted from those published in the literature varied significantly, and mean values were assumed for use in the LCA. The eCO_2 emissions of other materials and processes such as in reinforcing steel production, transportation of materials via trucks, and concrete batching were also based on data published in the literature. When determining the emissions generated per unit volume of concrete, the intermediate transportation requirements for the concrete production were calculated based on constant distances assumed between the aggregate extraction/processing facility and the concrete batching site. In future work, it will be critical to undertake a sensitivity analysis to understand the extent of the influence that transportation distances has on the overall building eCO_2 results.

The design work that was performed during this study revealed another area for future research work given that the compressive strength of the concrete was the only mechanical property considered. Structures were designed with 100% natural aggregate replacement with RCA using construction standards and guidelines that currently do not accommodate for these types of novel materials. A major assumption was made presuming that the only relevant design change in the concrete materials would be the compressive strength. However, multiple studies have shown that this is not necessarily the case when using RCA at such high replacement ratios (Butler, West, and Tighe 2011, Chinzorigt et al. 2020, Evangelista and Brito 2007, Xiao et al. 2012). Different properties such as the modulus of elasticity and time-dependent deformation mechanisms such as shrinkage and creep may also be significantly different for RCA compared to conventional concrete. Even the material resistance factor used in current limit states designs practice, which is meant to capture the variability in mechanical properties due to its production and placement, for conventional concrete structures (i.e., $\phi_c = 0.65$) may not be appropriate for use with these emerging sustainable materials.

5.2.4 Initial Conclusions and Recommendations Based on Pilot Study

Based on the results from this phase of the study involving the design and LCA of a potential medium-rise reinforced concrete office building, it was found that the use of RCA concrete can help reduce the environmental impact of new concrete construction but is dependent on the quality of the recycled material. With lower quality RCA derived from CDW, the reduced compressive strength of the resulting RCA concrete, resulted in reduced eCO_2 benefits because the use of these materials also required an increase in total material requirements (i.e., amount of concrete and reinforcing steel) for the structure. However, when using the higher quality RCA in RCA concrete, which led to no significant reductions in compressive strength, the resulting structural design required no adjustment relative to the control structure and therefore resulted in a much lower total eCO_2 value compared to both RCA concrete and the control structures. This study also led to several recommendations for future research in this emerging area, which include:

1. The selective use of RCA concrete in specific structural elements within a building (e.g., in slabs only) may yield significantly reduced eCO_2 emissions and needs to be investigated further.
2. Aside from the environmental impact category of CO_2 emissions, other areas of LCA need to be explored to determine whether they can provide a better measure of the overall benefits of RCA use in concrete.
3. As the structural design process used in this study was simplified, further investigation into the use of different design practices such as flat-slab floor systems should be evaluated.
4. As the use of 100% replacement of natural coarse aggregate with coarse RCA is not supported in most design codes and standards, the impact of this substitution needs to be further examined.

5.3 Need for Database

Based on the results from the pilot study, there were multiple changes that needed to be made to the process and design scenarios to produce better results going forward. From the two sources of

RCAs used in the initial study, it was seen that there is great variability in the compressive strength of concrete produced using RCA. To understand the range of compressive strengths which are typical when designing with RCA concrete, a list of results obtained from a large set of published research studies which included results related to the impact of RCA on the compressive strength of the resulting concrete was compiled.

5.4 Scope of Literature RCA Concrete Database

As a part of the literature review undertaken for this study, there was a significant amount of data collected from multiple published studies on the proportioning and the mechanical behaviour of concrete mixes utilising 100% CRCA (i.e., as a replacement of natural coarse aggregate). The information gathered was used to construct a database of 145 concrete mixtures with corresponding mix proportions, target compressive strengths, measured compressive strengths, compressive strength reductions from control (for RCA concrete mixes), and amount of eCO_2 per cubic meter of material. All concrete mixtures included in the database were extracted from studies where the compressive strength was recorded for both RCA and conventional concrete. The full database containing all 145 mixtures and corresponding data has been included in Appendix A.1.

5.5 Compressive Strength Variability Analysis

All RCA concrete mixtures from the studies examined (refer to Appendix A.1) were grouped into four compressive strength ranges based on the respective control mixture tested in each study. Compressive strength ranges included: 20 to 29 MPa, 30 to 39 MPa, 40 to 49 MPa, and 50+ MPa. For example, in a study where the control and RCA concrete mixture resulted in strengths of 30 and 28 MPa, respectively, the RCA mixture would belong to the 30 to 39 MPa range. For each study, the RCA concrete mixes were compared to the control mixture from the same study to calculate a strength reduction percentage. Table 5-3 presents the main compressive strength reduction values recorded for each strength range. For the purposes of this study, the three characteristic values of minimum, median, and maximum strength reduction were considered.

Table 5-3: Compressive Strength Reduction by Strength Range

Strength Reduction (compared with control mixture)				
Target f'$_c$ Range (MPa)	**20 - 29**	**30 - 39**	**40 - 49**	**50 - 60**
Minimum	0.0%	0.0%	0.0%	0.0%
Median	18.7%	9.7%	13.3%	11.6%
Maximum	26.2%	49.9%	22.4%	41.1%
Number of mixtures from literature review considered	17	34	16	23

In multiple instances, studies showed that when producing RCA concrete for testing with a specific target strength, if the RCA was of sufficient quality, the resulting concrete could surpass this target. This occurrence is also common practice in the design of conventional concrete mixtures where differences in manufacturing and environment factors along with conservative concrete production practices lead to concrete with much higher compressive strength than specified. When designing concrete structures, the actual value of concrete strength is not typically available, and the often much lower target value is used to provide required levels of conservatism. For the RCA concrete mixes where the strength was higher compared to the control concrete, the strength reduction percentage was taken as zero. The reason for this adjustment is that the RCA concrete in question was produced with the same target strength as the control mixes. As these mixes will be used for the design of a reinforced concrete structure and current building codes do not explicitly provide provisions for considering higher than the target (specified) compressive strength, this approach was deemed most appropriate.

Based on the results presented in Table 5-3, for 30-39 MPa RCA concrete the strength reduction ranges from 0-50% with a median reduction value of 9.7%. The mixes falling within the 50 to 60 MPa range had the second most data available (i.e., 23 mixtures) compared with the mixtures within the 30-39 MPa range (34 mixtures) . Due to the varying sources of original concrete, and differences in crushing and processing, the resulting quality of RCAs can vary widely. This variability is reflected in the findings presented in Table 5-3, which demonstrated that the compressive strength reduction for the RCA concrete mixtures was as high as 50% in some cases. By comparing the median strength reduction values, it can be seen that less significant reduction values as low as 9.7% were observed for RCA concrete. When disregarding compressive strength increases from RCA concrete, it was observed that the variability in compressive strength had no relation to the strength group. The compressive strength reduction was mainly governed by the types of RCA used rather that the target strength of the concrete mix.

5.6 Equivalent CO2 Variability Analysis

During the construction of this database of RCA concrete mixes, eCO_2 values were also generated for each concrete mixture. For each of the materials used in the production of the concrete (i.e., ordinary Portland cement, coarse and fine aggregates, water, etc.), a separate literature study was conducted to obtain representative eCO_2 values per unit weight of each constituent. Values for materials such as Portland cement, sand, and natural and RCA coarse aggregates were extracted from the relevant government and industry sources. Environmental product declarations published by several material suppliers to document the manufacturing impacts of their products were the primary source for the eCO_2 values used in this research. Emissions from intermediate processes such as concrete batching were obtained from other studies which focused on the lifecycle assessment for concrete production. Using this data for each concrete mixture, the eCO_2 emissions generated by the production of one cubic meter of concrete was recorded. Table 5-4 presents the characteristic minimum, median, and maximum eCO_2 emission values for each compressive strength range.

Table 5-4: Concrete eCO_2 Emissions by Strength Range

eCO_2 Emissions (kg eCO_2/m^3)				
Target f'_c Range (MPa)	**20 - 29**	**30 - 39**	**40 - 49**	**50 - 60**
Minimum	248.99	248.01	277.23	321.85
Median	287.11	324.79	361.88	412.76
Maximum	478.66	450.58	492.24	501.67
Number of mixtures from literature review considered	17	34	16	23

As shown, a clear trend is present in the data showing that as compressive strength increases, eCO_2 emissions also increase. This trend is due to the increased amount of Portland cement required to produce concrete of higher strength. Judging from the constructed database, eCO_2 emissions were found to vary greatly even within the same strength groups. The emissions presented in Table 5-4 each corresponded specific concrete mixes in the database which were used as characteristic mixes for the purpose of calculating eCO_2 values for concrete used later in the study. Note that detailed mixture proportions used to obtain the presented eCO_2 values have been included in Appendix A.1.

5.7 Conclusions

Following the pilot study which was conducted with the flat-plate concrete structure presented in Chapter 4, multiple new interesting variables and requirements emerged to be considered in the study. It was decided that the type of floor slab design and the elements in which RCA concrete was utilized and their effect on eCO_2 emissions would be important to explore going forward. Additionally, the need for an RCA concrete mix database was highlighted to determine reasonable RCA concrete compressive strength reductions and find mixes which would accurately represent concrete used in the construction industry for the purpose of calculating eCO_2 emissions.

CHAPTER 6: Building ECO$_2$ Emission Analysis for Multiple Scenarios

6.1 Overview

This chapter discusses the main group of 80 design scenarios analysed during the study for the comparison of eCO$_2$ emissions generated by the different structure types (i.e., flat plate or flat slab) and material transportation requirements. The chapter begins with the details of the analysis procedure used to determine emissions for each of the scenarios. Following the outline of the process, the 80 scenarios considered for the study are listed with a description of the differences. Finally, the results of the analysis are discussed and a set of conclusions are presented.

6.2 Integrated eCO$_2$ Emissions Analysis and Structural Design Framework

Based on the findings and lessons learned from the pilot study, an integrated eCO2 emissions analysis and structural design process was developed. The development of this process was based on several iterations and can be divided into three main parts. The first part involved developing a streamlined approach for making amendments to the design of the control (i.e., conventional concrete) structure to compensate for changes in concrete compressive strength when concrete of varying quality is substituted. The output of this first process provided the inventory of materials used in the construction of the simulated building. The second step is the calculation eCO$_2$ per unit (volume or weight) of material as outlined in the Chapter 3. Finally, the outputs of both processes were then used to determine the eCO$_2$ for the entire structure. Note that the pilot study considered only a limited number of design scenarios, and therefore, by implementing the developed integrated eCO$_2$ emissions analysis and structural design framework, numerous additional design scenarios could be considered and compared consistently. The proposed framework is presented in detail in Figure 6-1.

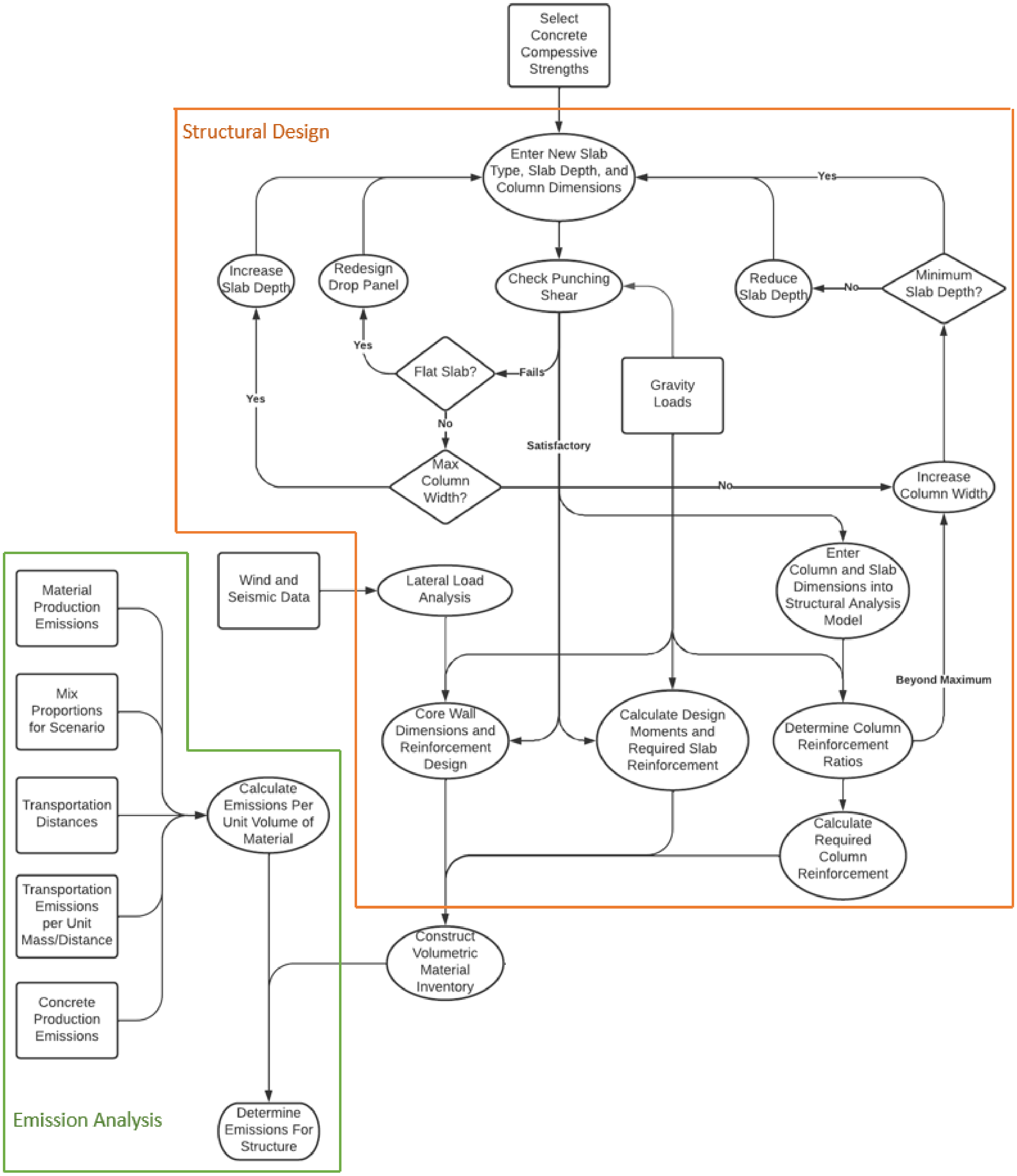


Figure 6-1: Integrated eCO$_2$ Emissions Analysis and Structural Design Framework

Each design scenario was analyzed using the process outlined in Figure 6-1. Given that 80 different design scenarios were considered, it was critical that the process be consistent as discussed in previous chapters. The process outlined in the framework begins with the selection of the concrete compressive strength for a given concrete mixture (conventional or RCA) being considered. Next, the structural floor system (i.e., flat plate or flat slab) is selected. With the self weight and superimposed deadloads determined, the slab is evaluated for two-way (punching) shear. If the selected slab fails at this point, depending on whether a flat slab or a flat plate floor system is chosen, changes are made to the column width or slab depth restarting the process. The adjustments to the design prioritized increasing drop panel depth or column size, when possible, rather than slab depth as this would lead to higher concrete use. After this check, the core wall design, and the initial slab and column reinforcement (based on the design of the control structure) are revised as necessary. The column reinforcement design is completed using the built-in reinforced concrete design features in SAP2000. If the column reinforcement was not sufficient, the process restarted from the second step with new column dimensions. Once all design checks have passed, the outputs from the design spreadsheets and the corresponding SAP2000 output values were used to produce a material inventory (i.e., total volume of concrete and total weight of reinforcing steel) for the scenario. Following the design process, the eCO_2 emissions were calculated for the materials used for the specific scenario. With both the unit emissions for materials and material inventory, the total building eCO_2 emissions were then calculated for each scenario. It is important to highlight that the structure evaluated in this research was a hypothetical reinforced concrete frame which was used to understand the interaction between RCA use and column, slab, shear wall, and drop panel design dimensions. As such details pertaining to the utilization of the structure with respect to building codes such as number of stairs required for the building were at times omitted from detailed consideration. In the future, more in depth consideration of building codes and how they affect the use of RCA concrete could be an interesting area of study.

6.3 Design Scenarios

Once the developed framework was finalized, multiple building design scenarios could be examined for comparing equivalent CO_2 emissions. Table 6-1 summarizes the eighty design scenarios that were analysed during this study. The design scenarios were grouped into four main categories based on the two design decisions made for the structure. The first of the decisions was the type of floor system used in the structure (flat plate or flat slab) while the second was the use of RCA concrete in the building. Half of the scenarios represent structures utilizing RCA concrete in all elements while the other half only use RCA concrete in the structural components requiring lower compressive strengths (20-30 MPa). The scenarios are further defined by the compressive strength performance of the RCA concrete and the transportation distances from the quarries/ recycling sites to the construction site for the coarse aggregates used. The distances ranged from 10 to 100 km based on real world transportation requirements observed in the literature.

Table 6-1A: Summary of Design Scenarios

Structure Type	Compressive Strength	Transportation Distance (km)	Scenario ID	Structure Type	Compressive strength	Transportation Distance (km)	Scenario ID
Flat Plate Floor System - All Elements Using RCA concrete	Control (30/50 MPa)	0	#01	**Flat Plate Floor System - Only Selected Elements Using RCA**	Control (30/50 MPa)	0	#41
		10	#02			10	#42
		25	#03			25	#43
		50	#04			50	#44
		100	#05			100	#45
	Low Quality RCA (20/30 MPa)	0	#06		Low Quality RCA (20/30 MPa)	0	#46
		10	#07			10	#47
		25	#08			25	#48
		50	#09			50	#49
		100	#10			100	#50
	Median Quality RCA (25/45 MPa)	0	#11		Median Quality RCA (25/45 MPa)	0	#51
		10	#12			10	#52
		25	#13			25	#53
		50	#14			50	#54
		100	#15			100	#55
	High Quality RCA (30/50 MPa)	0	#16		High Quality RCA (30/50 MPa)	0	#56
		10	#17			10	#57
		25	#18			25	#58
		50	#19			50	#59
		100	#20			100	#60

Table 6-1B: Summary of Design Scenarios Continued

Structure Type	**Compressive Strength**	**Transportation Distance (km)**	**Scenario ID**	**Structure Type**	**Compressive strength**	**Transportation Distance (km)**	**Scenario ID**
Flat Slab Floor System - All Elements Using RCA concrete	Control (30/50 MPa)	0	#21	**Flat Slab Floor System - Only Selected Elements Using RCA concrete**	Control (30/50 MPa)	0	#61
		10	#22			10	#62
		25	#23			25	#63
		50	#24			50	#64
		100	#25			100	#65
	Low Quality RCA (20/30 MPa)	0	#26		Low Quality RCA (20/30 MPa)	0	#66
		10	#27			10	#67
		25	#28			25	#68
		50	#29			50	#69
		100	#30			100	#70
	Median Quality RCA (25/45 MPa)	0	#31		Median Quality RCA (25/45 MPa)	0	#71
		10	#32			10	#72
		25	#33			25	#73
		50	#34			50	#74
		100	#35			100	#75
	High Quality RCA (30/50 MPa)	0	#36		High Quality RCA (30/50 MPa)	0	#76
		10	#37			10	#77
		25	#38			25	#78
		50	#39			50	#79
		100	#40			100	#80

6.4 Overall Material Quantity Results

6.4.1 Flat Plate Floor System

For the first set of three structures with flat plate floor systems, total building material quantities are presented in Table 6-2. As expected, the amount of concrete and steel required in the columns increases significantly with a reduction in concrete compressive strength as the axial compressive resistance of reinforced concrete columns is highly dependent on the compressive strength of the concrete. In the flat plate group, the volume of concrete stays constant while the steel required changes slightly due to alterations to the columns widths resulting in shorter clear spans. The volume of concrete required in the core walls also increases with the reduction in compressive strength.

Table 1-2: Concrete and reinforcing steel quantity summary (Flat plate floor system scenarios)

	Minimum Strength Reduction	Median Strength Reduction	Maximum Strength Reduction
Lower Strength Mix in Columns	251.6	331.3	446.9
Higher Strength Mix in Columns	288.9	380.4	513.1
Reinforcing Steel in Columns	**93380**	**98210**	**136045**
Lower Strength Mix in Slabs	3420	3420	3420
Higher Strength Mix in Slabs	158.4	158.4	158.4
Reinforcing Steel in Slabs	**260820**	**261625**	**255990**
Higher Strength Mix in Walls	671	704.6	805.2
Reinforcing in Walls	**11753**	**12397**	**14007**

*All concrete values in cubic meters

***All steel values in kilograms**

6.4.2 Flat Slab Floor System

The next set of design scenarios considered a flat slab structural floor system consisting of drop panels centered at each column. The total building material quantities for each of the flat slab structures are presented in Table 6-3. For this group of structures, the concrete requirements for the columns are lower compared to the flat slab structures and only increase at the maximum strength reduction. With the drop panels added to the building, the columns become smaller as punching shear is reduced. The required amount of steel reinforcement in the columns is higher compared to the flat plate floor system as a reduction in concrete compressive has a more significant effect on columns with smaller cross-sections.

Table 6-3: Flat-slab Full RCA Inventory

	Minimum Strength Reduction	Median Strength Reduction	Maximum Strength Reduction
Lower Strength Mix in Columns	226.0	226.0	293.8
Higher Strength Mix in Columns	259.5	259.5	337.3
Reinforcing Steel in Columns	**102235**	**141680**	**177905**
Lower Strength Mix in Slabs	3108.2	3108.2	3108.6
Higher Strength Mix in Slabs	116.8	122.6	145.6
Reinforcing Steel in Slabs	**285775**	**285775**	**280945**
Higher Strength Mix in Walls	671.0	738.1	838.8
Reinforcing in Walls	**11753**	**12960**	**14731**

*All concrete values in cubic meters

***All steel values in kilograms**

6.4.3 Selective Use of RCA Concrete

The third set of structures were designed to use both RCA and conventional concrete in certain structural elements to examine the effect on the overall building design and corresponding material quantities. Table 6-4 shows the total building material quantities for each of the concrete compressive strength classes. As the compressive strength of concrete is the most influential on the design of the columns and the core walls, it was decided to use RCA concrete for LSC and conventional concrete for HSC elements. As expected, the volume of the higher strength concrete used in the columns decreases slightly compared to the flat-plate full RCA material inventory results. However, with this approach, the design of the cross-sectional dimensions of the columns is still governed by punching shear experienced by the floor slabs and, therefore the column widths could not be significantly reduced.

Table 6-4: Flat-plate Partial RCA Inventory

	Minimum Strength Reduction	Median Strength Reduction	Maximum Strength Reduction
Lower Strength Mix in Columns	251.6	311.0	423.4
Higher Strength Mix in Columns	288.9	357.1	486.1
Reinforcing Steel in Columns	**93380**	**105455**	**91770**
Lower Strength Mix in Slabs	3420	3420	3420
Higher Strength Mix in Slabs	158.4	144.0	129.6
Reinforcing Steel in Slabs	**260820**	**260820**	**260015**
Higher Strength Mix in Walls	671	671	671
Reinforcing in Walls	**11753**	**11753**	**11753**

*All concrete values in cubic meters

***All steel values in kilograms**

A final group of structures were designed combining the use of a flat slab floor system with the selective use of RCA with the inventory presented in Table 6-5. In this set of structures, the concrete required for columns at minimum strength reduction is lower compared to the flat-plate design and stays constant throughout as the strength in the column elements is not reduced. With the addition of the drop panels, the width of the columns was not constrained by the punching shear requirements of the slab and the compressive strength of the conventional concrete could be utilized fully for more slender elements. The column steel reinforcing requirements were approximately 17% lower compared to the flat slab full RCA design. The volume of concrete required in both typical floor slabs and mechanical floor slab remained constant. This selective RCA utilization approach resulted in designs with the lowest volume of concrete compared to each of the scenarios examined thus far.

Table 6-5: Flat-slab Partial RCA Inventory

	Minimum Strength Reduction	Median Strength Reduction	Maximum Strength Reduction
Lower Strength Mix in Columns	226.0	226.0	226.0
Higher Strength Mix in Columns	259.5	259.5	259.5
Reinforcing Steel in Columns	**102235**	**117530**	**138460**
Lower Strength Mix in Slabs	3108.2	3108.2	3108.2
Higher Strength Mix in Slabs	116.8	116.8	116.8
Reinforcing Steel in Slabs	**285775**	**286580**	**288190**
Higher Strength Mix in Walls	671	671	671
Reinforcing Steel in Walls	**11753**	**11753**	**11753**

*All concrete values in cubic meters

***All steel values in kilograms**

6.5 Equivalent CO_2 Emissions Results

Once the material inventories were established for each scenario, the equivalent CO_2 values calculated before can be used to determine the emissions for each structure. Figure 6-2 presents the emissions of the first set of flat plate structures for each design and transportation scenario in a range. Considering the emissions with no transportation at 0 km shows very little improvement with the low strength RCA increasing the value and the best-case scenario of high strength RCA only showing minor reduction. However, as one of the main advantages of recycled aggregates is the reduced transportation requirements due to increased availability, it is reasonable to consider comparing values at different distances. Analysing a situation where natural concrete aggregate is obtained from a quarry 100 km away and recycled aggregates are available within 10 km of the site, the emissions from construction can be reduced by 3% using the low strength RCA. Considering the best-case scenario where the highest strength of RCA can be produced with the aggregates available, the reduction in emissions can go up to 13.7%.

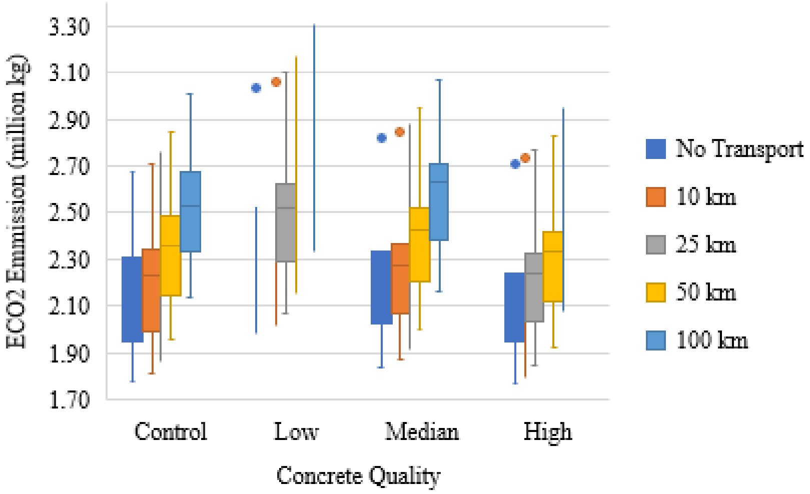


Figure 6-2: Flat-plate Full RCA eCO_2 Emissions by Concrete Quality (Compressive Strength)

Performing the same type of calculations for the material inventory generated during the design of the flat slab structure, the new emissions can be calculated as seen in Figure 6-3. Once again looking at the carbon emissions disregarding the transportation requirements, the highest strength RCA provides a minimal reduction in emissions. As with the flat plate structure, the transportation of 100 km for natural aggregates and 10 km for recycled aggregates can be compared. Examining the lowest strength RCA, there is a reduction of 3.9% in the carbon emissions generated during the construction of the building. In the best case where the RCA used is of a higher compressive strength, the emissions generated by a flat slab version of the structure can be reduced by up to 13.3%. It is interesting to note that although the volume of concrete material used in the flat slab structure is considerably lower compared to flat plate, it does not provide an improved performance in terms of emissions. This is due to the considerable increase in the amount of steel reinforcement required in the flat slab design.

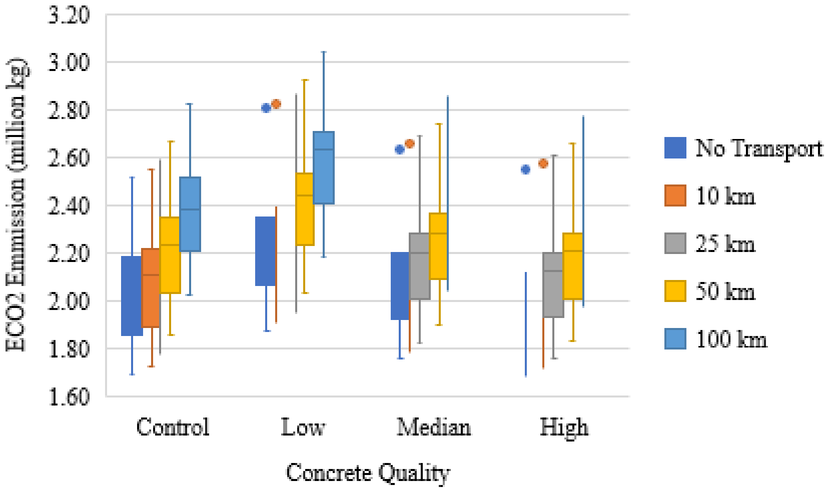


Figure 6-3: Flat-slab Full RCA Emissions by Concrete Quality (Compressive Strength)

Looking at the third set of design scenarios provided in Figure 6-4, the carbon emission performance of the selective RCA use can be seen. Not considering the contribution of material transportation, the higher strength RCA design can provide only a small decrease in the carbon emissions. Analysing the same altered transportation scenario seen the in the previous sets, the low strength RCA can reduce the emissions by 4.3%. With the highest compressive strength RCA, the equivalent carbon can be further reduced by up to 10.3%. Although the performance of the higher strength scenario is lower than that of the previous two sets analysed, it seems that the use of RCA selectively throughout the building provides a benefit in the case of the lower strength material. This indicates that the conventional concrete in the structure is helping reduce the reliance of the design on the RCA compressive strength while keeping and enhancing the benefits of reduced emissions with the recycled material.

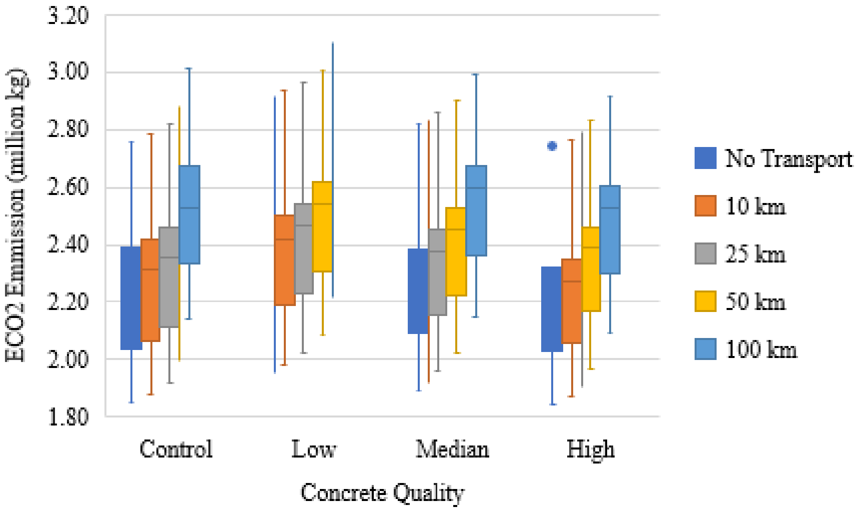


Figure 6-4: Flat-plate Partial RCA Emissions by Concrete Quality (Compressive Strength)

The final set of results presented in Figure 6-5 is the carbon emissions of structures using both a flat slab floor system with drop panels and selective RCA in the structural elements throughout the building. When the natural aggregates travel 100 km and the recycled aggregates are within 10 km, the emission reduction with the low strength RCA can be as high as 8%. With the high strength RCA, this reduction value goes up to 9.8%. From all four sets of design scenarios, it can be seen that the use of drop panels and selective RCA is the most beneficial way to utilise lower strength concrete.

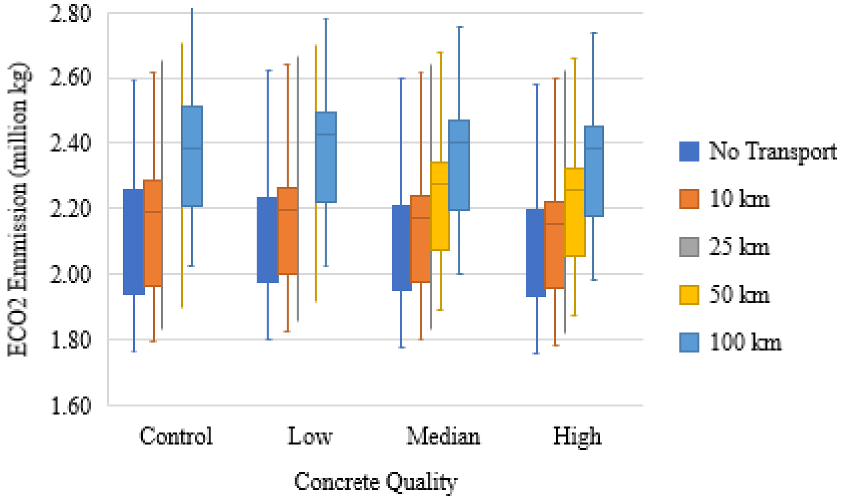


Figure 6-5: Flat-slab Partial RCA Emissions by Concrete Quality (Compressive Strength)

With the graphs presenting the range of emission values for each of the scenarios, it was found that the large variance in eCO_2 due to mix proportions is one of the main factors for determining the sustainability of the material produced. Although the following results in the research considered the median emission value for the material, further study of the relationship between RCA concrete mix design and eCO_2 would be helpful.

6.6 Design Scenario Comparison

To have a broader overview of the results, Figures 6-6 present the total emissions and eCO_2 reductions for each of the scenarios at different transportation requirements. Given different transportation scenarios for RCA availability, the potential reductions in eCO_2 emissions compared to natural aggregates available within 100 km of the site have been presented. The flat-plate and fully RCA structure shows a steep emission reduction increasing with the quality of RCA available. In the worst-case scenario when low quality RCA concrete is acquired within 50 km of the building site, an increase in emissions of approximately 4% was computed. In contrast, when high-quality RCA is available within 10 km of the building site, the eCO_2 can be reduced as much as 14%.

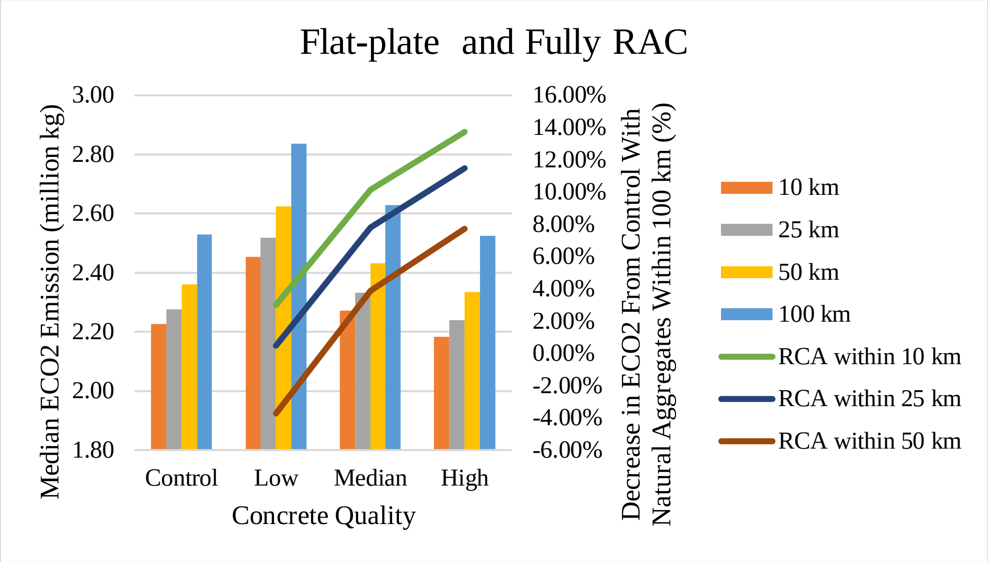


Figure 6-6: Flat-plate Full RCA Emission Reduction

Figure 6-7 presenting the same data for a flat-slab and fully RCA structure does not show much difference at the higher end of emission reduction still at 14%. However, the total building emissions with the low-quality RCA concrete seem to be slightly lower.

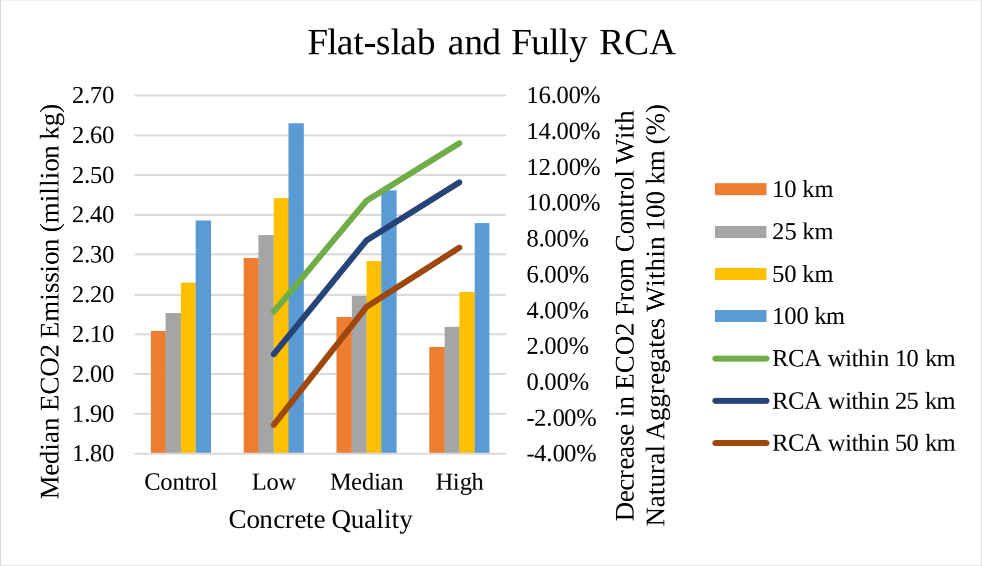


Figure 6-7: Flat-slab Full RCA Emission Reduction

The data for flat-plate and partially RCA structures presented in Figure 6-8 shows lower emission reduction values at 10% for the higher end for RCA quality and transportation distance. The worst case scenario becomes 0% reduction making RCA use a generally beneficial practice for sustainability in this type of structure.

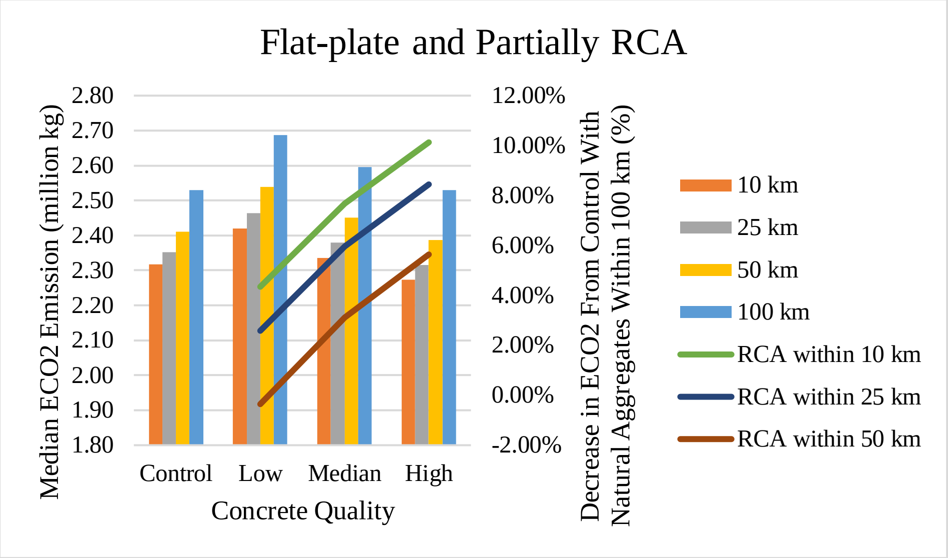


Figure 6-8: Flat-plate Partial RCA Emission Reduction

Finally, Figure 6-9 which presents data for flat-slab and partially RCA structures shows a much narrower range of emission reduction factors compared to the rest of the scenarios. Although emission reduction at the higher end is slightly lower at 10% compared to fully RCA structures, the use of lower quality RCA shows better sustainability outcomes.

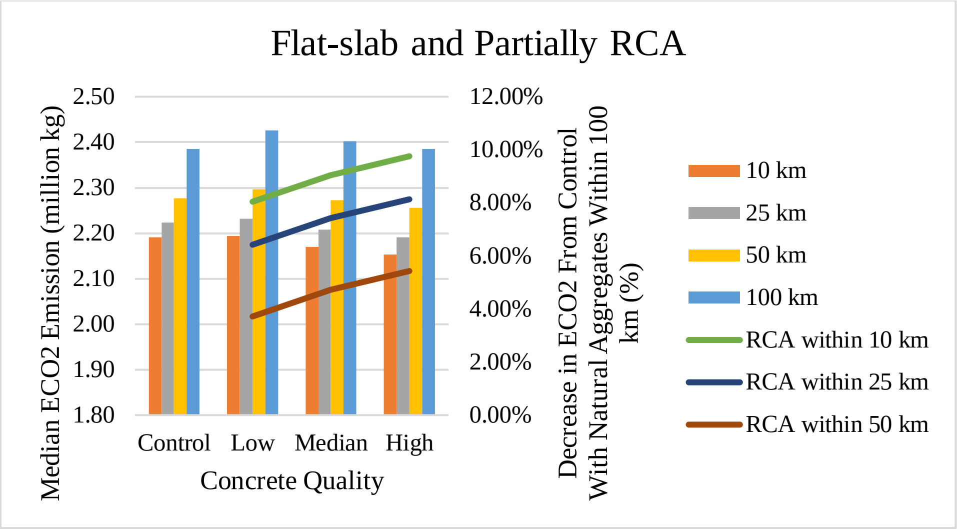


Figure 6-9: Flat-slab Partial RCA Emission Reduction

To make better comparisons between different design scenarios, the total eCO$_2$ emissions results for all scenarios are presented in Figure 6-10.

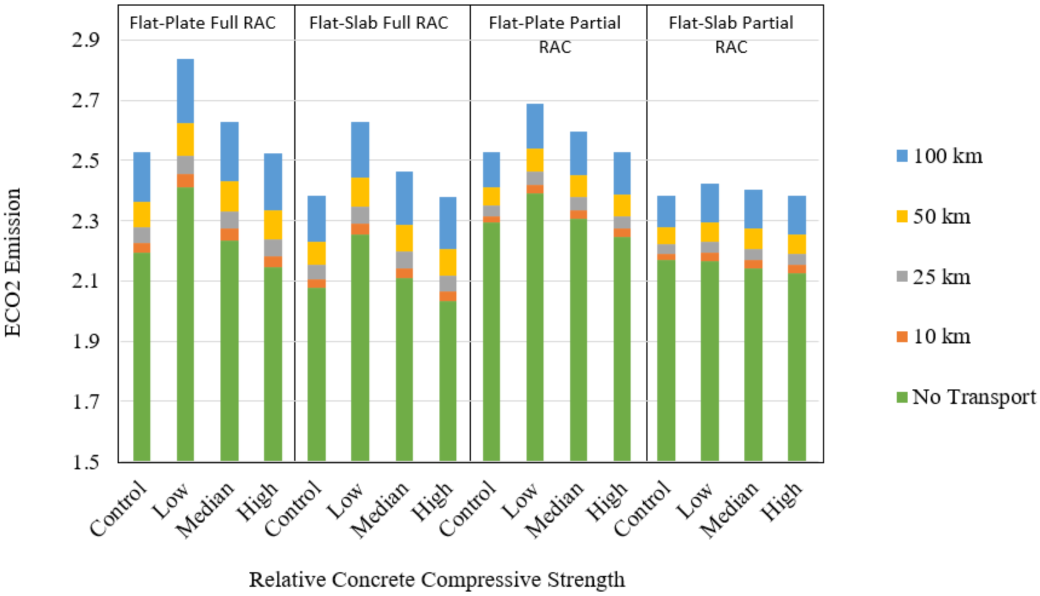


Figure 6-10: Total Building eCO$_2$ Emissions for All Design Scenario

Of all design scenarios evaluated, the combination of low-quality RCA concrete used in a flat-plate fully RCA concrete structure resulted in the highest total building eCO$_2$ emissions. This was expected since with the flat plate design the reduction in compressive strength is detrimental to the punching shear resistance requiring either deeper floor slabs or wider columns to satisfy preliminary checks. Similarly using RCA concrete in all elements including the higher strength columns at the base of the structure results in wider columns as the reduction id compressive strength negatively impacts the capacity of the columns. The carbon emissions for flat-slab full RCA structures are lower in general but still unfavorable for lower quality RCAs. In the case of flat-plate partially RCA structures, the difference between lower and higher quality RCAs are slightly smaller but the overall emissions are higher compared to before. Finally, flat-slab partially RCA structures provide the lowest emission values for low to median quality RCAs. For the high-quality RCA concrete which was assumed to have the same compressive strength at conventional concrete, the flat-slab full RCA case presented the lowest eCO_2 emissions.

6.7 Conclusions

By analysing the results of each of the design scenarios and their corresponding eCO_2 emissions, multiple observations can be made on the use of RCAs in reinforced concrete construction:

1. The sustainability of the RCA material depends heavily on the quality of the concrete that can be produced. As the source and content of the RCA is an important factor, the availability, and the best approach to benefiting from the reduction in eCO_2 needs to be considered on a case-by-case basis for each project.
2. It can be seen through the results that although the low quality RCA concrete produced inferior concrete (as compared to the corresponding conventional concrete) which leads to increase member dimension and/or reinforcing steel quantities, and a corresponding increase in total building eCO_2 emissions. With reduced transportation requirements for materials that can be obtained closer to the construction site, even with lower strength concrete, a small reduction

in eCO_2 emissions can still be achieved. When analysing the scenario where natural aggregates need to be transported 100 km while RCAs are available within 10 km, even with the lowest grade RCA concrete strength, reductions in total building eCO_2 emissions ranging between 3 and 8% were calculated.

3. The type of structural floor system used is also one of the main factors determining the sustainability of the RCA concrete. For the highest quality RCA concrete, changing from a flat plate to a flat slab floor structure led to an overall increase in total building eCO2 emissions. However, with the lowest quality RCA concrete, the reduction in carbon emissions increased from 3% to 4% with the introduction of drop panels (i.e., in the case of a flat slab floor system). This implies that when the quality of RCA available is a constraint for a project, designers may want to avoid flat plate structures in order to maximize their sustainability benefit.
4. Another scenario analysed was the selective use of RCA concrete throughout the building to improve the strength of members which were disproportionately effected by the lower compressive strength of the material. Compared to the initial flat-plate design as well as the flat-slab design, this method had the lowest reduction in eCO_2 emissions for the highest quality of RCA at 10.3%. However, compared to these two cases, it had the highest reduction in eCO_2 emissions for the low-quality RCA at 4.3%. Similar to the results of the flat-slab scenario, this shows that changing designs to make selective use of RCA concrete when the quality of the material is an issue can be helpful in reducing the overall building eCO_2 emissions. This type of change also has the advantage of being easier to implement as it does not constrain the type of structural system that can be used.
5. The final scenario examined a structure designed using both a flat-slab floor system and selective use of RCA concrete. Once again, the results presented higher eCO_2 for high quality

RCA, but for low quality RCA concrete this combination resulted in the highest eCO_2 emissions reduction of 8% compared with all other scenarios. Considering a reinforced concrete building project where the structural floor system and concrete material type are not constrained, this would be the best design scenario for maximising the sustainability of a structure utilising RCA concrete.

CHAPTER 7: Evaluation of the Trade-Offs Between Reducing eCO_2 and Overall Construction Costs

7.1 Overview

This chapter presents the results of the comparison of eCO_2 emissions and construction costs for the various design scenarios presented in Chapter 6. First, background is provided for the importance of this type of analysis and how it aligns with the overall framework of this research. More details are provided on how the cost estimation process was performed for each of the structures considered. The eCO_2 emissions and cost data is then compiled to provide a better understanding of the trade-offs as well as optimization considerations between overall project cost and associated eCO_2 footprint. In addition to the previously introduced design scenarios, three hypothetical real-world case study examples are proposed and analysed using the developed framework of this thesis.

7.2 Background and Framework for the Integrated eCO_2 and Construction Cost Structural Design of RCA Concrete Structures

Although the reduction of pollutants such as carbon dioxide in the atmosphere is essential for mitigating the overall effects of climate change, minimizing the eCO_2 footprint of a new building alone is not the main consideration in its design and construction. As in many industries, all new innovations (e.g., new sustainable materials) that seek to reduce the environmental impacts of different processes will eventually be judged for feasibility by the financial costs of implementation. Therefore, at this stage of the research, it was decided that an analysis of costs with respect to each scenario considered previously would provide valuable insight into the practicality and overall feasibility of implementing RCA concrete in new construction. This consideration for financial cost was therefore combined within the existing analysis framework to produce a more comprehensive emissions and cost analysis design framework which is illustrated using Figure 7-1. Previous iterations of the framework contained the steps related to the design of the structure and calculation of eCO_2 emissions for materials. In this new version the cost analysis section was included with describes the use of concrete material, transportation and labour costs obtained from RSMeans data. With the input of the volumetric material inventory determined in the previous step, this data is used to estimate the cost of construction for the structure.

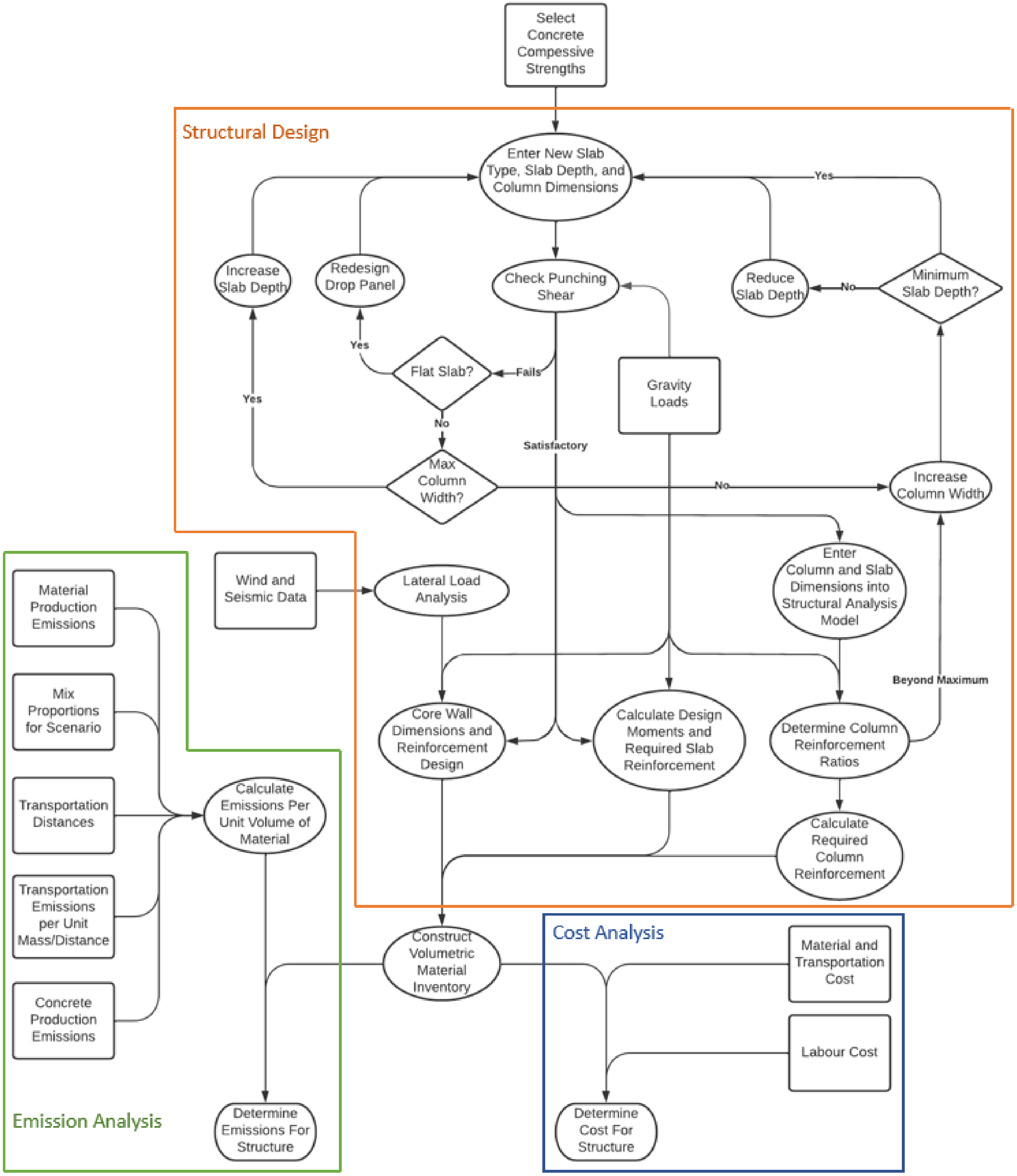


Figure 7-1: Integrated eCO_2 Emissions Analysis and Structural Design Framework with Construction Cost Considerations

7.3 Estimation of Overall Construction Costs

The construction costs for the structures in each design scenario were calculated using costing data from the 2021 RS Means Database for Building Construction Costs (2021). The cost data provides pricing by unit weight of materials (e.g., aggregates, cement, reinforcing steel, etc.) and total material weights were extracted from the material inventories constructed previously. For materials accounting for the majority of the building mass (i.e., fine and coarse aggregates) transportation costs associated with these materials were also included in the overall cost. Concrete forming and placing costs were also determined based on the volume and surface area of the structural elements. The estimation of cost for materials was performed by multiplying the material requirements obtained from each design with the unit costs obtained from the RS Means database. Labour related costs such as concrete forming and placing required dimensions from the design such as height and surface area of different structural elements (e.g., slabs, walls, etc.) which were also determined during the design process. The transportation costs were computed based on the distance and weight of material being transported. The distance was provided by the scenario being considered (i.e., 0 km, 10 km, 25 km, 50 km or 100 km) and the mass of material was determined from the design and the concrete mixture proportions (i.e., in order to compute the associated quantities of aggregates and cement). Certain transportation distances used for materials such as fine aggregates were assumed to be constant as they were not the focus of this study and these values were the same assumed when calculating eCO_2 emissions.

7.4 Construction Costs of Design Scenarios

The cost of materials and labour required for the construction was calculated for each of the 80 scenarios considered. The cost of each structure is presented in Figure 7-2 in dollars (CAD).

Overall, the cost of each design scenario ranged between $5.3 million and $6.0 million when only considering materials and labour. The lowest cost was observed for the structures utilising flat-plate designs utilizing conventional concrete or high-quality RCA concrete either fully or partially throughout the building. The worst cases for cost were the scenarios using low quality RCA concrete in every member with either flat plate or flat slab design at $5.8 and $6.0 million, respectively. The use of a flat slab designs showed a clear disadvantage with respect to costs with the lowest values at around $5.6 million even when utilizing high-quality RCA concrete. This presented a deviation from previous trend when analyzing the total building eCO_2 emissions where flat slab structures contained lower eCO_2 emission values due to the reduced material requirements. This increase in construction cost was mainly attributed to the higher cost of concrete forming for flat-slab structures.

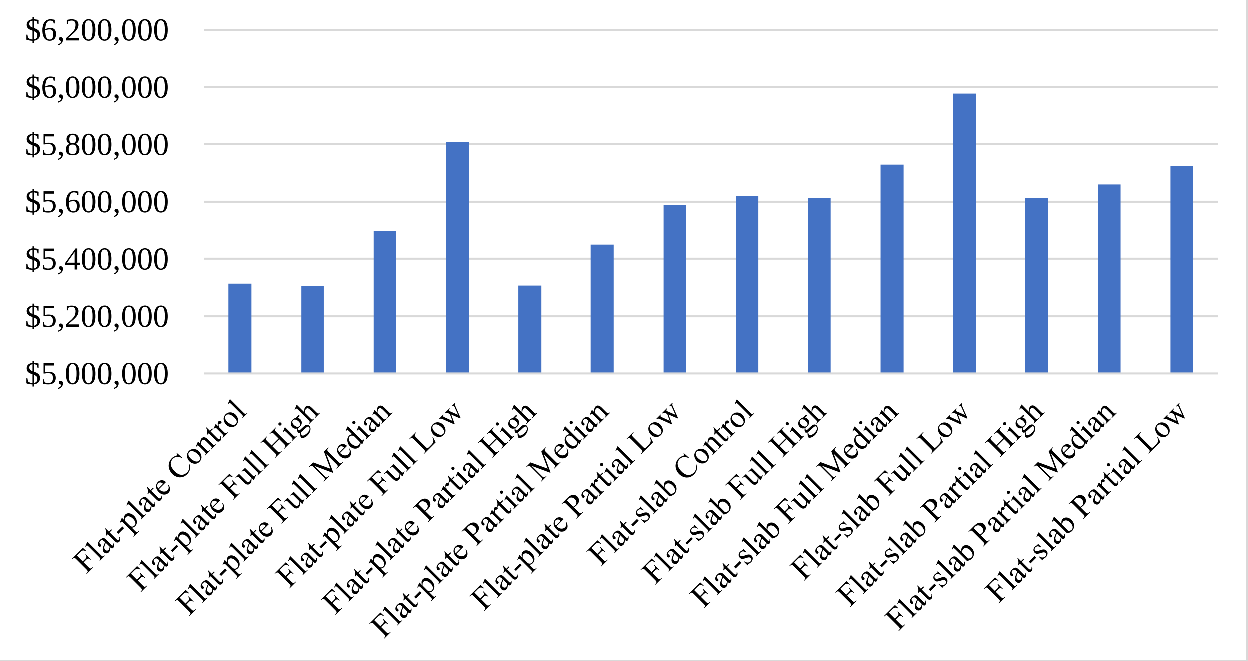


Figure 7-2 Summary of materials and labour costs for each design scenario

When calculating the cost of concrete using RSMeans data, the cost of $26.10 (USD) is provided per ton of natural aggregates. As this study has centered around the utilization of RCA in concrete, the difference in material costs between natural aggregates and RCA needed to be quantified. Given that the 2021 RSMeans database does not provide unit costs for RCA, it was decided that the price differences between natural and RCA could be better understood through the examination of studies in the literature. Thus, three different studies which have investigated the cost differences between NA and RCA were analysed. Most examples presented a decrease in costs when using RCA instead of NCA ranging from a 19 to 57% reduction (Ohemeng et al., Kurda et al.) in aggregate cost. In one instance, the RCA had a 46% increase (Bostanci et al.) in cost, highlighting the large variance in the price of RCA compared to NCA. To have a better understanding of the effects of this variability in cost, Figure 7-3 presents the costs of materials and labour previously determined with the addition of RCA price ranges (-57% to +46%). As the quantity of RCA concrete used in design scenarios incorporating RCA concrete in all structural elements, this cost variation has a smaller effect on partial RCA scenarios. In order to understand the impact of this change in RCA cost on the total construction cost, the percentage changes from the base aggregate cost were calculated for the variations. Based on the overall cost of the project, the variance in aggregate cost can at most result in a cost reduction of around 1.2% or a cost increase of 1.0%. For cost estimation calculations, individual materials seem to have less overall contribution due to the influence of labour and construction related factors such as concrete forming and placing. The subsequent calculations of construction costs were performed assuming no price difference between RCA and natural aggregates production.

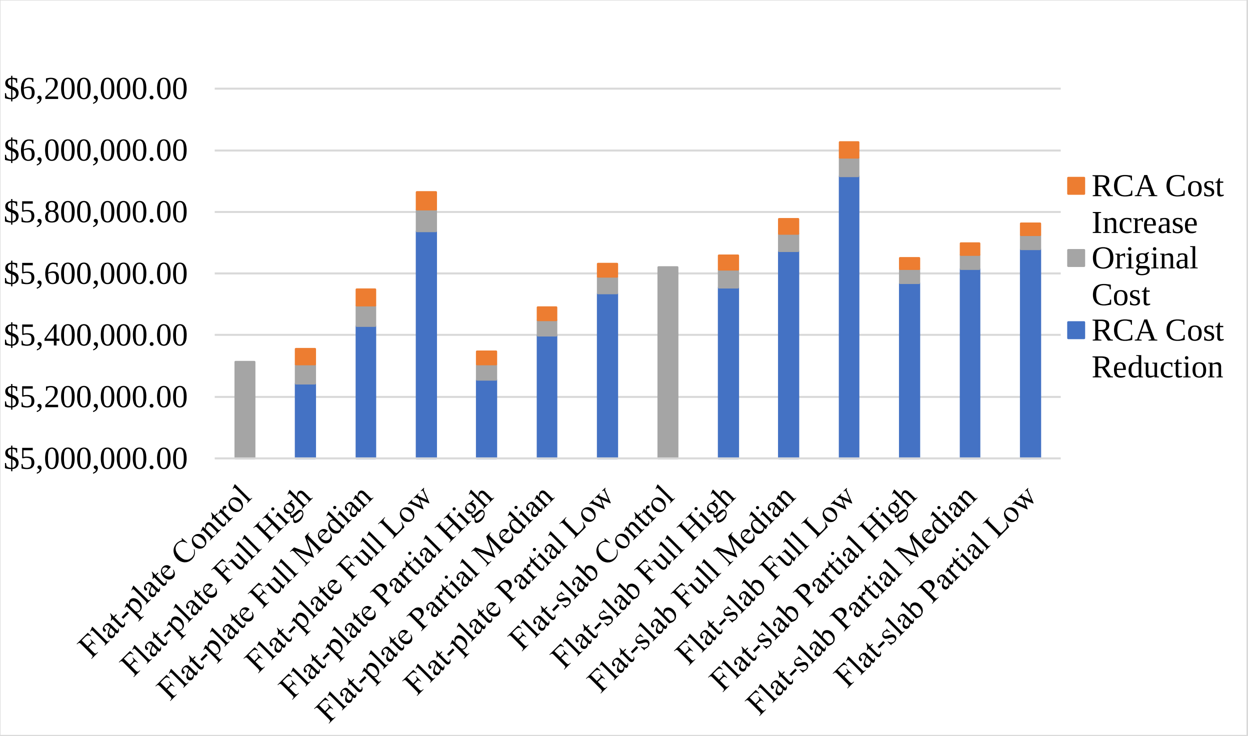


Figure 7-3: Cost of Materials and Labour + RCA Price Change Compared to Natural Aggregates for Each Design Scenario

7.4.1 Incorporation of Material Transportation Costs

Similar to the eCO_2 emissions results presented in Chapter 6, the effect of material transportation distance must be considered when calculating the overall construction cost of the project. The RSMeans data provides costs by weight of materials for a given transportation distance which was used to determine the costs for each design scenario. To facilitate a more valid comparison between eCO_2 emissions and construction costs (later in this chapter), all assumptions made regarding transportation requirements were kept constant as per those detailed in Chapter 6. Figure 7-4 presents the project cost for each type of structure with the addition of costs resulting from increasing transportation requirements compared to the original cost without transportation considerations. With the worst case scenario of 100 km of transportation distance for coarse aggregates, the cost was shown to increase by up to 3% as compared to the control structure. This worst case scenario presents an increase in construction costs of almost $200 thousand for any scenario. Once again, since this increase in cost is related to the volume of materials used, the impact to construction cost is less prominent. In comparison to eCO_2 emissions the increase to cost due to transportation is less significant.

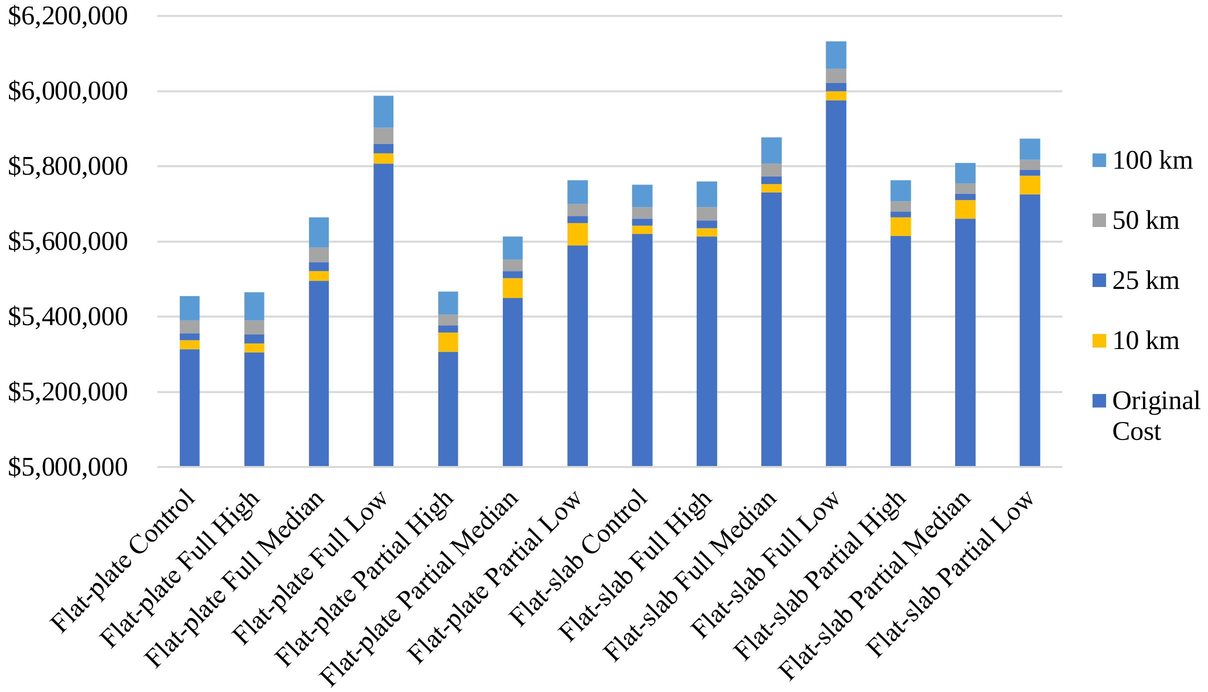
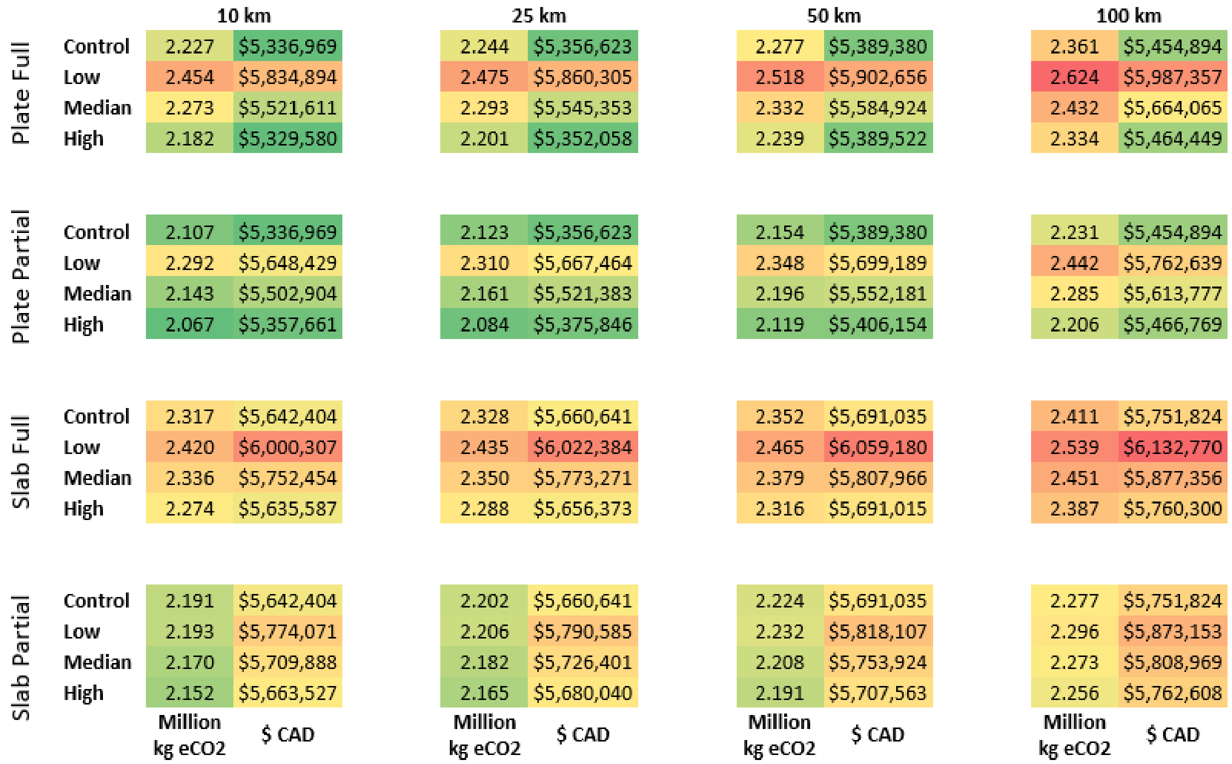


Figure 7-4: Cost of Materials and Labour + Four Different Levels of Transportation Requirements for Each Design Scenario

7.5 Comparing Design Scenario eCO_2 Emissions and Overall Construction Costs

After calculating the costs for each of the structures considering multiple transportation distances, the values were compared to the eCO_2 emissions analyzed in Chapter 6. Table 7-1 shows a table of construction costs and eCO_2 emissions for each scenario listed together for comparison. Each value of cost and eCO_2 was color coded separately with red being the highest in order to visually highlight the worst- and best-case scenarios when considering both metrics. With the data presented as such, observations could be made based on the trade-offs of each of the scenarios analysed. Overall, scenarios including flat-plate structures with partial utilization of RCA concrete were found to have better performance in terms of both construction costs and eCO_2 emissions. In design scenarios which assumed the availability of high-quality RCA concrete (with no reduction in compressive strength compared with the equivalent conventional concrete), the partial RCA concrete and flat-plate structure presented the optimal scenario (i.e., a combination of lowest eCO_2 emissions and lowest overall construction cost). Although cost of construction had a slight increase compared to the full RCA and flat-plate structures, the values were still in the lowest end (dark green), with also the lowest eCO_2 recorded. In scenarios where median-quality RCA concrete is available, the flat-plate partial RCA concrete structure remained as the optimal design. In contrast to the high-quality RCA concrete scenario, both the construction costs and eCO_2 emissions were the lowest for the median quality RCA concrete for this type of structure. Overall, flat-slab structures which utilized RCA concrete in all structural elements, resulted in the highest eCO_2 emissions and highest construction costs making them the least desirable of design scenarios. In scenarios where only low-quality RCA concrete is available, it was observed that a flat-slab structures which partially utilized RCA concrete resulted in the lowest eCO_2 emission values. However, this reduction in eCO_2 emissions also corresponded to higher construction cost compared to the flat-plate partial RCA structures. Additionally, since the emission values were closer to the higher end (light green), there would have to be a significantly lower transportation requirements to make RCA use beneficial.

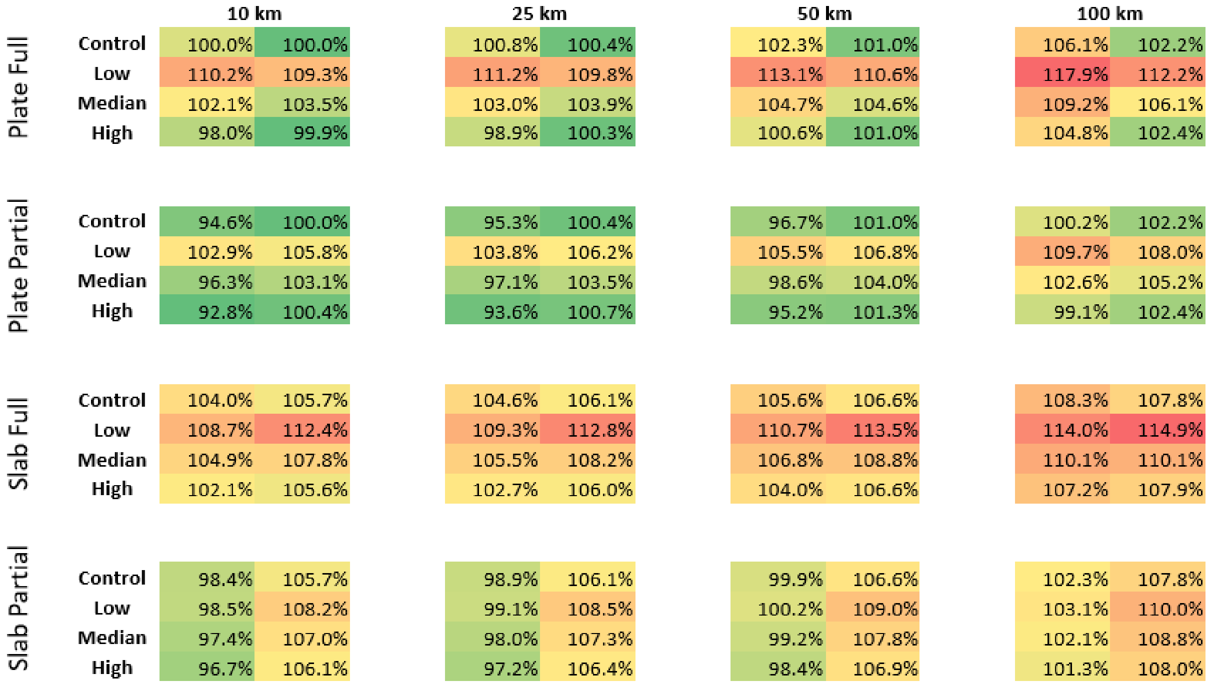
Table 7-1: Comparison of Costs and Emissions for Each Scenario



		10 km		25 km		50 km		100 km	
Plate Full	Control	2.227	$5,336,969	2.244	$5,356,623	2.277	$5,389,380	2.361	$5,454,894
	Low	2.454	$5,834,894	2.475	$5,860,305	2.518	$5,902,656	2.624	$5,987,357
	Median	2.273	$5,521,611	2.293	$5,545,353	2.332	$5,584,924	2.432	$5,664,065
	High	2.182	$5,329,580	2.201	$5,352,058	2.239	$5,389,522	2.334	$5,464,449
Plate Partial	Control	2.107	$5,336,969	2.123	$5,356,623	2.154	$5,389,380	2.231	$5,454,894
	Low	2.292	$5,648,429	2.310	$5,667,464	2.348	$5,699,189	2.442	$5,762,639
	Median	2.143	$5,502,904	2.161	$5,521,383	2.196	$5,552,181	2.285	$5,613,777
	High	2.067	$5,357,661	2.084	$5,375,846	2.119	$5,406,154	2.206	$5,466,769
Slab Full	Control	2.317	$5,642,404	2.328	$5,660,641	2.352	$5,691,035	2.411	$5,751,824
	Low	2.420	$6,000,307	2.435	$6,022,384	2.465	$6,059,180	2.539	$6,132,770
	Median	2.336	$5,752,454	2.350	$5,773,271	2.379	$5,807,966	2.451	$5,877,356
	High	2.274	$5,635,587	2.288	$5,656,373	2.316	$5,691,015	2.387	$5,760,300
Slab Partial	Control	2.191	$5,642,404	2.202	$5,660,641	2.224	$5,691,035	2.277	$5,751,824
	Low	2.193	$5,774,071	2.206	$5,790,585	2.232	$5,818,107	2.296	$5,873,153
	Median	2.170	$5,709,888	2.182	$5,726,401	2.208	$5,753,924	2.273	$5,808,969
	High	2.152	$5,663,527	2.165	$5,680,040	2.191	$5,707,563	2.256	$5,762,608
		Million kg eCO2	$ CAD	Million kg eCO2	$ CAD	Million kg eCO2	$ CAD	Million kg eCO2	$ CAD

To help in better understanding the changes to the overall eCO_2 and construction costs, Table 7-2 presents the cost and emission results as a percentage of the values obtained for the flat-plate control design scenario (for the 10 km transportation distance). With this, the benefits from higher quality RCA sources can be better understood. For the best case scenario for eCO_2 emissions, the mass is reduced by 7.2% from control while the cost of construction only increases by 0.4% from control. When only low quality RCA is available the best that can be achieved is 1.5% reduction in eCO_2 emissions with an 8.2% increase to cost. This underlines the importance of the RCA quality in best utilizing the material for concrete construction.

Table 7-2: Comparison of Costs and Emissions for Each Scenario as a Percentage of Flat-plate Control 10 km



		10 km		25 km		50 km		100 km	
Plate Full	Control	100.0%	100.0%	100.8%	100.4%	102.3%	101.0%	106.1%	102.2%
	Low	110.2%	109.3%	111.2%	109.8%	113.1%	110.6%	117.9%	112.2%
	Median	102.1%	103.5%	103.0%	103.9%	104.7%	104.6%	109.2%	106.1%
	High	98.0%	99.9%	98.9%	100.3%	100.6%	101.0%	104.8%	102.4%
Plate Partial	Control	94.6%	100.0%	95.3%	100.4%	96.7%	101.0%	100.2%	102.2%
	Low	102.9%	105.8%	103.8%	106.2%	105.5%	106.8%	109.7%	108.0%
	Median	96.3%	103.1%	97.1%	103.5%	98.6%	104.0%	102.6%	105.2%
	High	92.8%	100.4%	93.6%	100.7%	95.2%	101.3%	99.1%	102.4%
Slab Full	Control	104.0%	105.7%	104.6%	106.1%	105.6%	106.6%	108.3%	107.8%
	Low	108.7%	112.4%	109.3%	112.8%	110.7%	113.5%	114.0%	114.9%
	Median	104.9%	107.8%	105.5%	108.2%	106.8%	108.8%	110.1%	110.1%
	High	102.1%	105.6%	102.7%	106.0%	104.0%	106.6%	107.2%	107.9%
Slab Partial	Control	98.4%	105.7%	98.9%	106.1%	99.9%	106.6%	102.3%	107.8%
	Low	98.5%	108.2%	99.1%	108.5%	100.2%	109.0%	103.1%	110.0%
	Median	97.4%	107.0%	98.0%	107.3%	99.2%	107.8%	102.1%	108.8%
	High	96.7%	106.1%	97.2%	106.4%	98.4%	106.9%	101.3%	108.0%

7.6 Real World Case Study Examples and Optimization Considerations

To better demonstrate how the Integrated eCO$_2$ Emissions Analysis and Structural Design Framework with Construction Cost Considerations developed as part of this research could be applied to help determine the feasibility of using RCA concrete in new construction, three real world case study examples based on building sites at various locations across Ontario, Canada were devised. The parameters for each scenario were selected to provide contrast in RCA quality, associated construction materials, impact of regional climate/environment, labour costs, and transportation distances of natural aggregates and RCAs.

7.6.1 Case Study Example #1 – Highly Urbanized Setting

The building site location chosen for the first case study example structure was in downtown Toronto. This represented a highly developed urban center with natural aggregates available a moderate distance from the building site. Considering construction and demolition activities would be relatively active in these areas, high-quality RCA was assumed to be readily available close to the site of the project. The following is a summary of the parameters considered in this example:

1) Building site location: Toronto (downtown), Ontario
2) Distance to nearest concrete aggregate quarry: 62 km
3) RCA Availability: median-quality RCA source available within 10 km and high-quality RCA available within 25 km

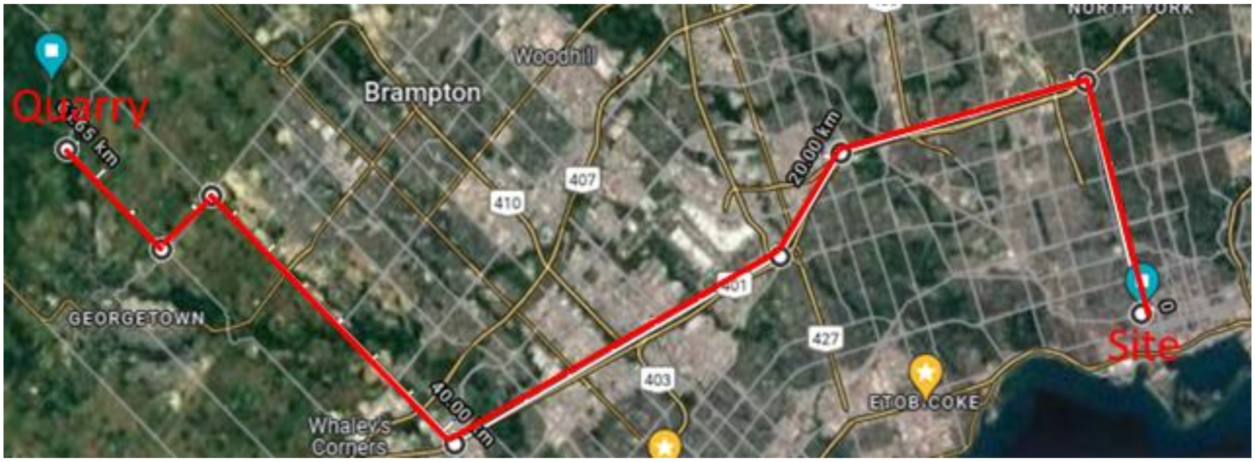
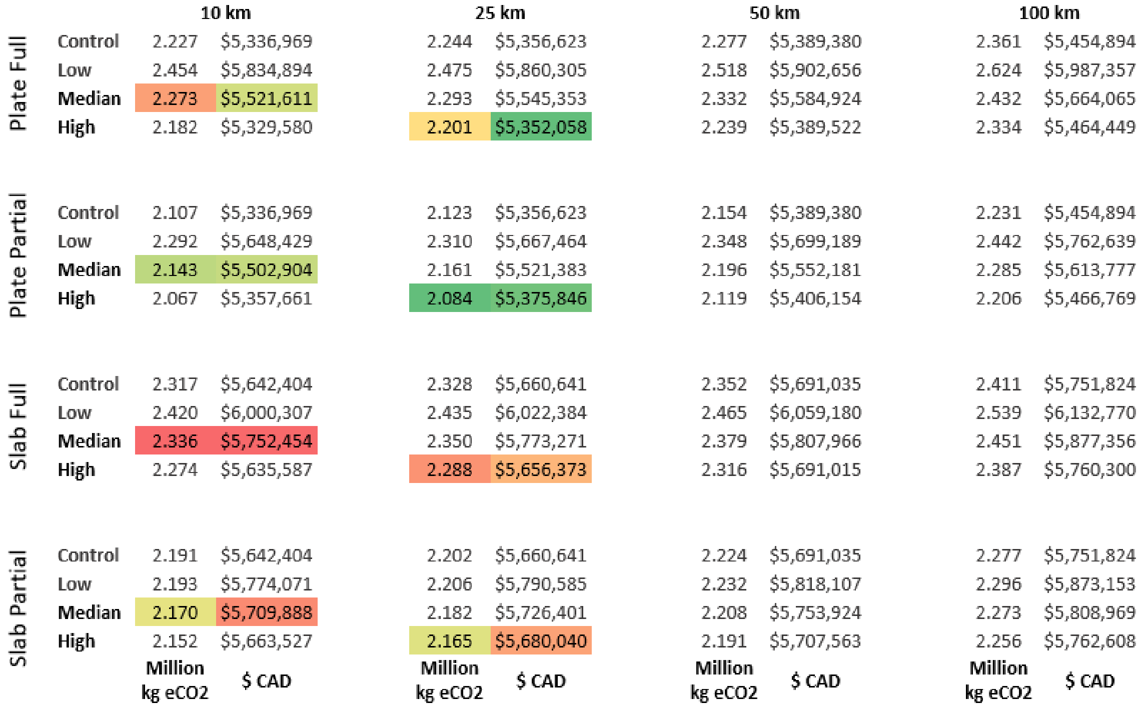


Figure 7-5: Image of First Study Area with Distance Marker – Quarry Top Left, Site Bottom Right (Google Maps)

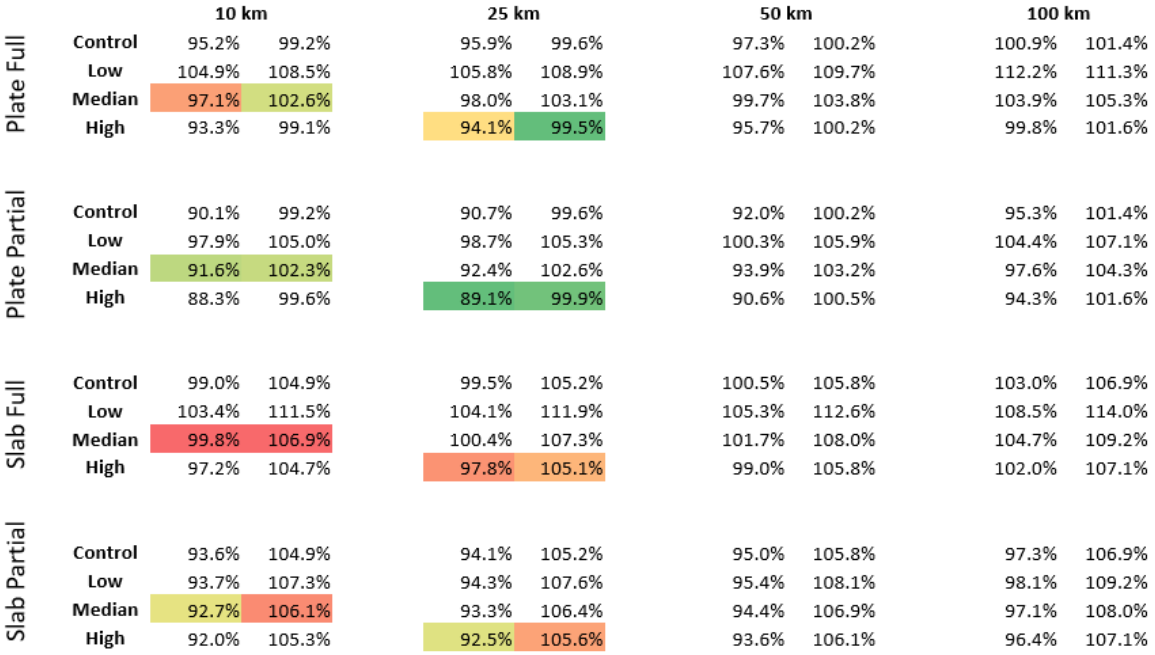
With the nearest aggregate quarry located 62 km from the building site, the cost of the control structure was determined to be \$5.380 million and \$5.683 million for the flat-plate and flat-slab designs, respectively. Additionally, the eCO_2 emissions for the control structure was calculated to be 2.34 million kg and 2.21 million kg for the flat-plate and flat-slab structures, respectively. In order to be a viable option, the costs and emissions calculated for each of the RCA concrete scenarios would have to be lower than these target values. Table 7-3 shows each of the specific scenarios being considered for the RCA concrete structures in this example. The scenarios including flat-plate structures with RCA concrete utilized partially in low strength structural elements, result in the lowest eCO_2 emissions for both the median and high quality aggregate sources. Using median quality aggregates was observed to increase the cost of the structure from the control, but with high quality RCA the cost was reduced. The fully RCA flat-slab options were deemed unviable as the only value lower than the control was the cost with high quality RCA. The partial use of RCA concrete had better results for a flat-slab design compared to the fully RCA scenarios with only the costs for median quality RCA increasing from control. The best case scenario with respect to emissions was determined to be the flat-plate structure with partial RCA concrete utilization. Table 7-4 shows the costs and emissions as a percentage of the flat-plate control values to better judge the performance of each option. For the best case scenario where high quality RCA is available within 25 km, the eCO_2 emission is reduced by 10.9% compared to the NA structure with no increase in construction cost. In this example the optimal choice was found to be the partial high quality RCA flat plate structure which had the lowest emission and no increase in cost.

Table 7-3: Comparison of Costs and Emissions for Scenarios Considered in Case Study Example #1



		10 km		**25 km**		**50 km**		**100 km**	
Plate Full	Control	2.227	$5,336,969	2.244	$5,356,623	2.277	$5,389,380	2.361	$5,454,894
	Low	2.454	$5,834,894	2.475	$5,860,305	2.518	$5,902,656	2.624	$5,987,357
	Median	2.273	$5,521,611	2.293	$5,545,353	2.332	$5,584,924	2.432	$5,664,065
	High	2.182	$5,329,580	2.201	$5,352,058	2.239	$5,389,522	2.334	$5,464,449
Plate Partial	Control	2.107	$5,336,969	2.123	$5,356,623	2.154	$5,389,380	2.231	$5,454,894
	Low	2.292	$5,648,429	2.310	$5,667,464	2.348	$5,699,189	2.442	$5,762,639
	Median	2.143	$5,502,904	2.161	$5,521,383	2.196	$5,552,181	2.285	$5,613,777
	High	2.067	$5,357,661	2.084	$5,375,846	2.119	$5,406,154	2.206	$5,466,769
Slab Full	Control	2.317	$5,642,404	2.328	$5,660,641	2.352	$5,691,035	2.411	$5,751,824
	Low	2.420	$6,000,307	2.435	$6,022,384	2.465	$6,059,180	2.539	$6,132,770
	Median	2.336	$5,752,454	2.350	$5,773,271	2.379	$5,807,966	2.451	$5,877,356
	High	2.274	$5,635,587	2.288	$5,656,373	2.316	$5,691,015	2.387	$5,760,300
Slab Partial	Control	2.191	$5,642,404	2.202	$5,660,641	2.224	$5,691,035	2.277	$5,751,824
	Low	2.193	$5,774,071	2.206	$5,790,585	2.232	$5,818,107	2.296	$5,873,153
	Median	2.170	$5,709,888	2.182	$5,726,401	2.208	$5,753,924	2.273	$5,808,969
	High	2.152	$5,663,527	2.165	$5,680,040	2.191	$5,707,563	2.256	$5,762,608
		Million kg eCO2	**$ CAD**	**Million kg eCO2**	**$ CAD**	**Million kg eCO2**	**$ CAD**	**Million kg eCO2**	**$ CAD**

Table 7- 4: Comparison of Costs and Emissions for Scenarios Considered in Case Study Example #1 as a Percentage of Flat-plate Control 62 km



		10 km		**25 km**		**50 km**		**100 km**	
Plate Full	**Control**	95.2%	99.2%	95.9%	99.6%	97.3%	100.2%	100.9%	101.4%
	Low	104.9%	108.5%	105.8%	108.9%	107.6%	109.7%	112.2%	111.3%
	Median	97.1%	102.6%	98.0%	103.1%	99.7%	103.8%	103.9%	105.3%
	High	93.3%	99.1%	94.1%	99.5%	95.7%	100.2%	99.8%	101.6%
Plate Partial	**Control**	90.1%	99.2%	90.7%	99.6%	92.0%	100.2%	95.3%	101.4%
	Low	97.9%	105.0%	98.7%	105.3%	100.3%	105.9%	104.4%	107.1%
	Median	91.6%	102.3%	92.4%	102.6%	93.9%	103.2%	97.6%	104.3%
	High	88.3%	99.6%	89.1%	99.9%	90.6%	100.5%	94.3%	101.6%
Slab Full	**Control**	99.0%	104.9%	99.5%	105.2%	100.5%	105.8%	103.0%	106.9%
	Low	103.4%	111.5%	104.1%	111.9%	105.3%	112.6%	108.5%	114.0%
	Median	99.8%	106.9%	100.4%	107.3%	101.7%	108.0%	104.7%	109.2%
	High	97.2%	104.7%	97.8%	105.1%	99.0%	105.8%	102.0%	107.1%
Slab Partial	**Control**	93.6%	104.9%	94.1%	105.2%	95.0%	105.8%	97.3%	106.9%
	Low	93.7%	107.3%	94.3%	107.6%	95.4%	108.1%	98.1%	109.2%
	Median	92.7%	106.1%	93.3%	106.4%	94.4%	106.9%	97.1%	108.0%
	High	92.0%	105.3%	92.5%	105.6%	93.6%	106.1%	96.4%	107.1%

7.6.2 Case Study Example #2 – Sub-Urbanized Setting

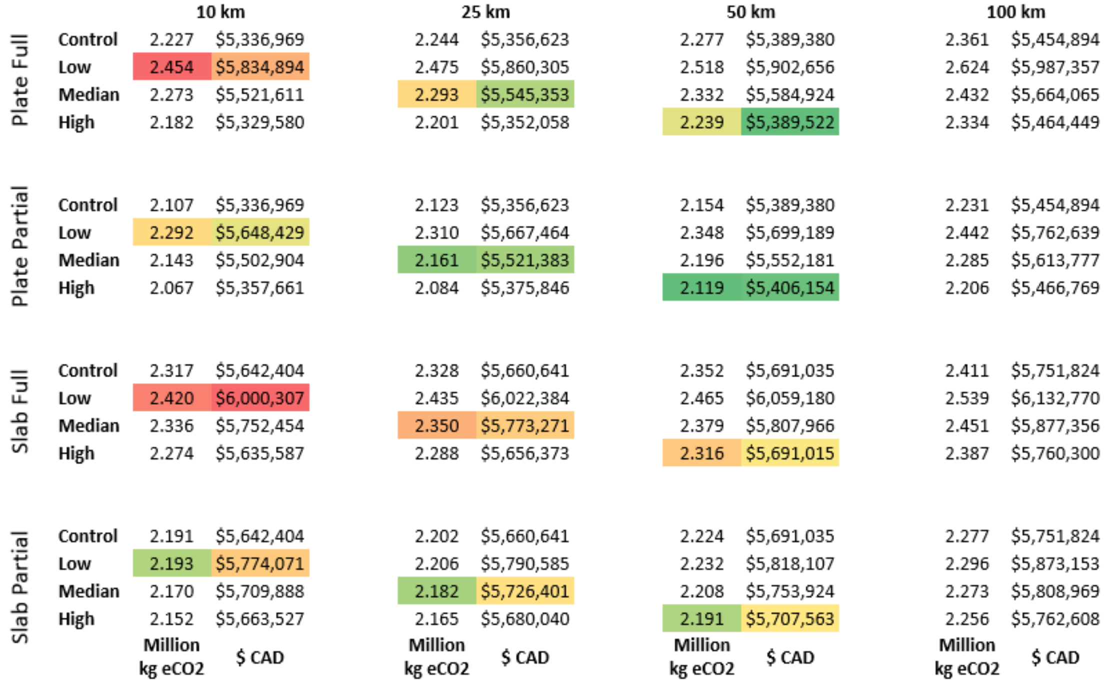
The second building site considered was located within a suburban center with natural aggregates in close proximity. This example was selected to represent the most disadvantageous scenario for considering using RCA concrete. In this example low, median, and high quality RCA were assumed to be available within 10, 25, and 50 km of the site, respectively. The availability of higher-quality RCA was reduced in this scenario as the location chosen was further away from a highly developed urban center whereby a larger variety of concrete demolition waste would be available. The following is a summary of the parameters considered in this example:

1) Building site location: Brampton, Ontario
2) Distance to nearest concrete aggregate quarry: 18 km
3) RCA availability: low quality RCA available within 10 km median-quality available within at 25 km, and high-quality available within 50 km

Figure 7-6: Image of Second Study Area with Distance Marker – Quarry Left, Site Right (Google Maps)

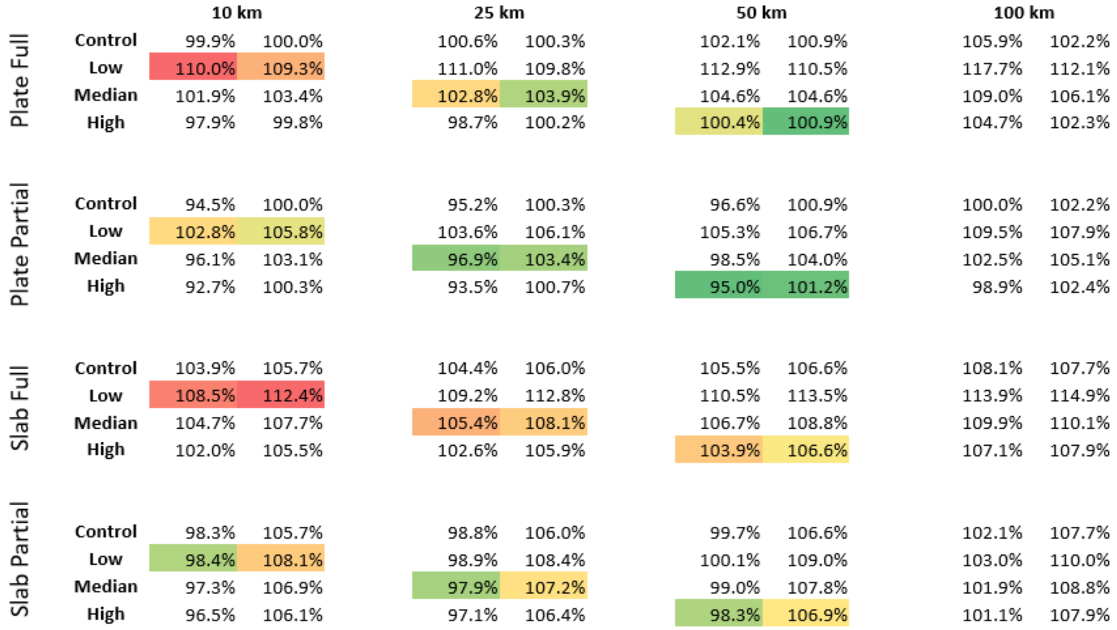
With the nearest concrete stone quarry at a distance of 18 km, the cost of the control structure was determined to be \$5.340 million CAD and \$5.645 million CAD for the flat-plate and flat-slab designs respectively. The eCO_2 emissions for the natural aggregate structure was calculated to be 2.23 million kg and 2.11 million kg for the flat-plate and flat-slab structures respectively. Table 7-5 shows each of the specific design and transportation scenarios being considered for the RCA structure in this example with the same color coding as before. In this example, with the higher availability of natural aggregates, an increase to cost was determined unavoidable using RCA. However, with the use of higher quality RCA, although the distance from the site has increased the cost increase can be minimised. The best case scenario was found to be the flat-plate partial RCA structure using the high quality aggregate source. This combination resulted in a 5% decrease to eCO_2 emission while only increasing the cost of the structure by 1.2%. As the distance to a natural aggregate source was low, the use of low quality RCA was found to be unsuitable as emissions and costs were higher in all cases. Table 7-6 shows the costs and emissions for the project as a percentage of the flat-plate control values to better judge the performance of each option.

Table 7-5: Comparison of Costs and Emissions for Scenarios Considered in the Second Example



		10 km		25 km		50 km		100 km	
Plate Full	Control	2.227	$5,336,969	2.244	$5,356,623	2.277	$5,389,380	2.361	$5,454,894
	Low	2.454	$5,834,894	2.475	$5,860,305	2.518	$5,902,656	2.624	$5,987,357
	Median	2.273	$5,521,611	2.293	$5,545,353	2.332	$5,584,924	2.432	$5,664,065
	High	2.182	$5,329,580	2.201	$5,352,058	2.239	$5,389,522	2.334	$5,464,449
Plate Partial	Control	2.107	$5,336,969	2.123	$5,356,623	2.154	$5,389,380	2.231	$5,454,894
	Low	2.292	$5,648,429	2.310	$5,667,464	2.348	$5,699,189	2.442	$5,762,639
	Median	2.143	$5,502,904	2.161	$5,521,383	2.196	$5,552,181	2.285	$5,613,777
	High	2.067	$5,357,661	2.084	$5,375,846	2.119	$5,406,154	2.206	$5,466,769
Slab Full	Control	2.317	$5,642,404	2.328	$5,660,641	2.352	$5,691,035	2.411	$5,751,824
	Low	2.420	$6,000,307	2.435	$6,022,384	2.465	$6,059,180	2.539	$6,132,770
	Median	2.336	$5,752,454	2.350	$5,773,271	2.379	$5,807,966	2.451	$5,877,356
	High	2.274	$5,635,587	2.288	$5,656,373	2.316	$5,691,015	2.387	$5,760,300
Slab Partial	Control	2.191	$5,642,404	2.202	$5,660,641	2.224	$5,691,035	2.277	$5,751,824
	Low	2.193	$5,774,071	2.206	$5,790,585	2.232	$5,818,107	2.296	$5,873,153
	Median	2.170	$5,709,888	2.182	$5,726,401	2.208	$5,753,924	2.273	$5,808,969
	High	2.152	$5,663,527	2.165	$5,680,040	2.191	$5,707,563	2.256	$5,762,608
		Million kg eCO2	$ CAD	Million kg eCO2	$ CAD	Million kg eCO2	$ CAD	Million kg eCO2	$ CAD

Table 7-6: Comparison of Costs and Emissions for Scenarios Considered in the Second Example as a Percentage of Flat-plate Control 18 km



		10 km		25 km		50 km		100 km	
Plate Full	Control	99.9%	100.0%	100.6%	100.3%	102.1%	100.9%	105.9%	102.2%
	Low	110.0%	109.3%	111.0%	109.8%	112.9%	110.5%	117.7%	112.1%
	Median	101.9%	103.4%	102.8%	103.9%	104.6%	104.6%	109.0%	106.1%
	High	97.9%	99.8%	98.7%	100.2%	100.4%	100.9%	104.7%	102.3%
Plate Partial	Control	94.5%	100.0%	95.2%	100.3%	96.6%	100.9%	100.0%	102.2%
	Low	102.8%	105.8%	103.6%	106.1%	105.3%	106.7%	109.5%	107.9%
	Median	96.1%	103.1%	96.9%	103.4%	98.5%	104.0%	102.5%	105.1%
	High	92.7%	100.3%	93.5%	100.7%	95.0%	101.2%	98.9%	102.4%
Slab Full	Control	103.9%	105.7%	104.4%	106.0%	105.5%	106.6%	108.1%	107.7%
	Low	108.5%	112.4%	109.2%	112.8%	110.5%	113.5%	113.9%	114.9%
	Median	104.7%	107.7%	105.4%	108.1%	106.7%	108.8%	109.9%	110.1%
	High	102.0%	105.5%	102.6%	105.9%	103.9%	106.6%	107.1%	107.9%
Slab Partial	Control	98.3%	105.7%	98.8%	106.0%	99.7%	106.6%	102.1%	107.7%
	Low	98.4%	108.1%	98.9%	108.4%	100.1%	109.0%	103.0%	110.0%
	Median	97.3%	106.9%	97.9%	107.2%	99.0%	107.8%	101.9%	108.8%
	High	96.5%	106.1%	97.1%	106.4%	98.3%	106.9%	101.1%	107.9%

7.6.3 Case Study Example #3 – Newly Urbanized Setting

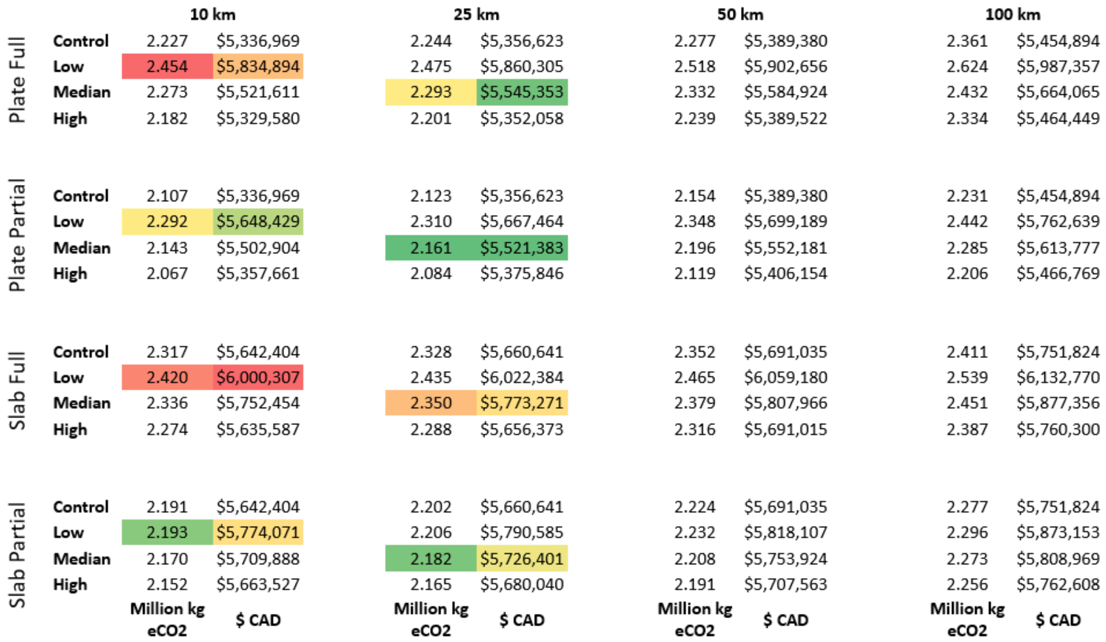
The third example location was chosen to represent a newly developing and remote urban area to determine the feasibility of utilizing RCA concrete in geographical regions with few urbanized areas The nearest source of natural aggregates was found to be approximately 30 km away. Since this location was not near a highly developed urban center, the availability of higher-quality RCA was assumed to be limited. The following is a summary of the parameters considered in this example:

1) Building site location: Sudbury, Ontario – 34 km to nearest quarry
2) Distance to nearest concrete aggregate quarry: 34 km
3) RCA availability: high-quality RCA not available, median-quality RCA available within 25 km and low-quality RCA available within 10 km

Figure 7-7: Location of Third Study Area (Sudbury, Ontario) with Distance Markers to nearest concrete aggregate quarry – Quarry Top Left, Sudbury Site Right (Google Maps)

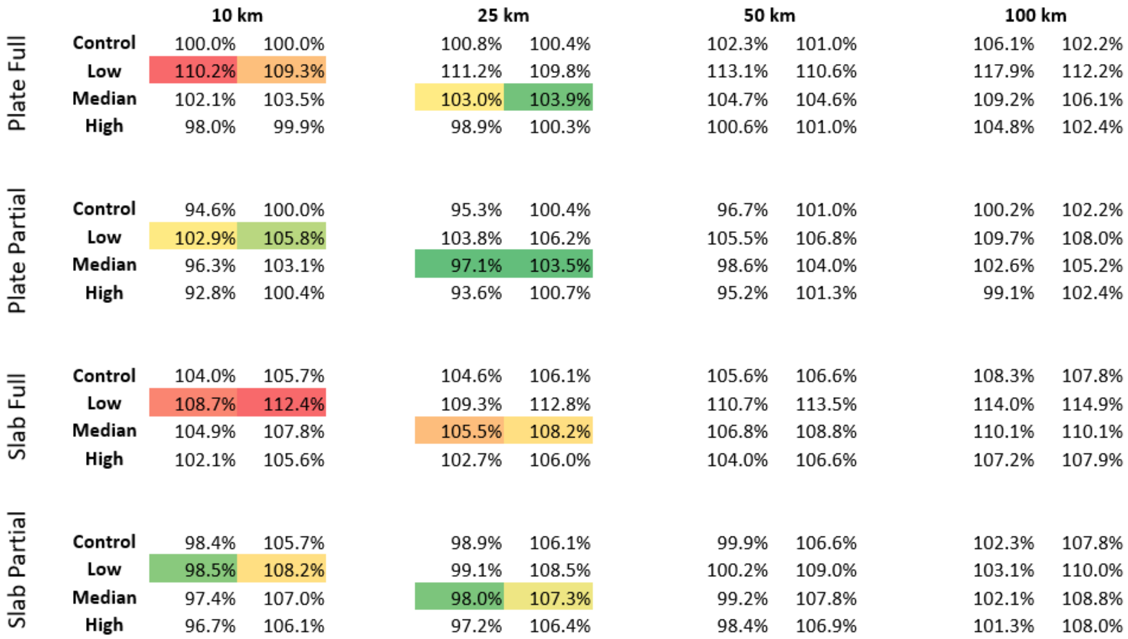
The cost of the control structure was determined to be $5.363 million CAD and $5.667 million CAD for the flat-plate and flat-slab designs respectively. The eCO_2 emissions for the natural aggregate structure was calculated to be 2.29 million kg and 2.17 million kg for the flat-plate and flat-slab structures respectively. Although in this example high quality aggregates were assumed to be unavailable, a reduction to eCO_2 emissions was possible using median quality aggregates. Once again, the flat-plate structure partially using RCA concrete was found to be the best case scenario with a 3% reduction in emissions. However, with high-quality RCA unavailable, the costs of the structures incorporating RCA were found to increase in each of the scenarios considered. Therefore, the use of lower quality RCA in this particular region may not be feasible from a cost standpoint.

Table 7-7: Comparison of Costs and Emissions for Scenarios Considered in the Third Example



		10 km		25 km		50 km		100 km	
		Million kg eCO2	$ CAD	Million kg eCO2	$ CAD	Million kg eCO2	$ CAD	Million kg eCO2	$ CAD
Plate Full	Control	2.227	$5,336,969	2.244	$5,356,623	2.277	$5,389,380	2.361	$5,454,894
	Low	2.454	$5,834,894	2.475	$5,860,305	2.518	$5,902,656	2.624	$5,987,357
	Median	2.273	$5,521,611	2.293	$5,545,353	2.332	$5,584,924	2.432	$5,664,065
	High	2.182	$5,329,580	2.201	$5,352,058	2.239	$5,389,522	2.334	$5,464,449
Plate Partial	Control	2.107	$5,336,969	2.123	$5,356,623	2.154	$5,389,380	2.231	$5,454,894
	Low	2.292	$5,648,429	2.310	$5,667,464	2.348	$5,699,189	2.442	$5,762,639
	Median	2.143	$5,502,904	2.161	$5,521,383	2.196	$5,552,181	2.285	$5,613,777
	High	2.067	$5,357,661	2.084	$5,375,846	2.119	$5,406,154	2.206	$5,466,769
Slab Full	Control	2.317	$5,642,404	2.328	$5,660,641	2.352	$5,691,035	2.411	$5,751,824
	Low	2.420	$6,000,307	2.435	$6,022,384	2.465	$6,059,180	2.539	$6,132,770
	Median	2.336	$5,752,454	2.350	$5,773,271	2.379	$5,807,966	2.451	$5,877,356
	High	2.274	$5,635,587	2.288	$5,656,373	2.316	$5,691,015	2.387	$5,760,300
Slab Partial	Control	2.191	$5,642,404	2.202	$5,660,641	2.224	$5,691,035	2.277	$5,751,824
	Low	2.193	$5,774,071	2.206	$5,790,585	2.232	$5,818,107	2.296	$5,873,153
	Median	2.170	$5,709,888	2.182	$5,726,401	2.208	$5,753,924	2.273	$5,808,969
	High	2.152	$5,663,527	2.165	$5,680,040	2.191	$5,707,563	2.256	$5,762,608

Table 7-8: Comparison of Costs and Emissions for Scenarios Considered in the Third Example as a Percentage of Flat-plate Control 34 km



		10 km		25 km		50 km		100 km	
Plate Full	Control	100.0%	100.0%	100.8%	100.4%	102.3%	101.0%	106.1%	102.2%
	Low	110.2%	109.3%	111.2%	109.8%	113.1%	110.6%	117.9%	112.2%
	Median	102.1%	103.5%	103.0%	103.9%	104.7%	104.6%	109.2%	106.1%
	High	98.0%	99.9%	98.9%	100.3%	100.6%	101.0%	104.8%	102.4%
Plate Partial	Control	94.6%	100.0%	95.3%	100.4%	96.7%	101.0%	100.2%	102.2%
	Low	102.9%	105.8%	103.8%	106.2%	105.5%	106.8%	109.7%	108.0%
	Median	96.3%	103.1%	97.1%	103.5%	98.6%	104.0%	102.6%	105.2%
	High	92.8%	100.4%	93.6%	100.7%	95.2%	101.3%	99.1%	102.4%
Slab Full	Control	104.0%	105.7%	104.6%	106.1%	105.6%	106.6%	108.3%	107.8%
	Low	108.7%	112.4%	109.3%	112.8%	110.7%	113.5%	114.0%	114.9%
	Median	104.9%	107.8%	105.5%	108.2%	106.8%	108.8%	110.1%	110.1%
	High	102.1%	105.6%	102.7%	106.0%	104.0%	106.6%	107.2%	107.9%
Slab Partial	Control	98.4%	105.7%	98.9%	106.1%	99.9%	106.6%	102.3%	107.8%
	Low	98.5%	108.2%	99.1%	108.5%	100.2%	109.0%	103.1%	110.0%
	Median	97.4%	107.0%	98.0%	107.3%	99.2%	107.8%	102.1%	108.8%
	High	96.7%	106.1%	97.2%	106.4%	98.4%	106.9%	101.3%	108.0%

7.7 Conclusions

After the estimation of costs for each of the design scenarios discussed and comparison of these costs with the eCO_2 emissions previously presented, several significant conclusions were made:

1. When calculating the total construction costs, the type of structural floor system utilised was more significant compared to the use of material. Due to the labour associated costs of flat-slab structures such as concrete forming, the cost of construction for these designs were higher than designs utilizing flat-plate construction. In contrast, when calculating the eCO_2 emissions, the contributions of the individual materials (i.e., concrete and reinforcing steel) were more significant, leading to reduction in total building emissions when using flat-slab designs with low-quality RCA. As a result, it was observed that when using lower quality RCA to reduce eCO_2 emissions, there will be an increase to the overall construction cost of the structure for both flat-plate and flat-slab structures.
2. With different sources of RCA, it was observed that there may be changes to the cost of the material used. RCA with lower quality might be cheaper than the natural alternative, while higher quality RCA from specific sources or with treatments can have a higher cost. Without a reliable method of judging the changes to the cost of different types of RCA, an uncertainty of 1-1.2% was observed when calculating the cost of construction.
3. The costs of material transportation were also observed to have a small impact on the overall cost of construction. In the worst-case scenario where coarse aggregates need to be transported from 100 km away, the overall construction cost of the structure was found to increase by up to only 3%.
4. Comparing the costs and the emissions for each of the design scenarios, the lowest costs and eCO_2 for high- and median-quality RCA were in flat-plate structures utilizing RCA

concrete in part of the structure with a maximum increase of 5.2% in construction costs. For low-quality RCA, the lowest computed eCO_2 emissions were attributed to the flat-slab design which utilized RCA concrete in part of the structure. This resulted in a maximum increase of 10% in overall construction cost.

5. With respect to the example construction cases, the use of high quality RCA sources with flat-plate structures and RCA concrete used only in lower strength members resulted in the lowest eCO_2 emissions and costs in all instances regardless of transportation requirements. This shows that for designs aiming to utilize RCA concrete, the selection of RCA sources with high quality should be prioritized. At this level of quality where the RCA does not impact the compressive strength of the concrete negatively, much higher transportation requirements can be allowed before the emissions and costs begin to increase past the control values.
6. From the case study examples, when lower quality RCA was available with reduced transportation requirements, emissions reductions were observed but costs were significantly higher. The use of this grade of RCA should only be considered when higher quality alternatives are not available within a much larger range and make the use of RCA undesirable with respect to costs.

CHAPTER 8: Conclusions and Recommendations for Future Work

8.1 Overview

This chapter presents a summary of the conclusions made throughout this thesis. Following the concluding observations from each individual phase of the research, the overall conclusions and remarks from each phase are presented. The last section of the chapter discusses areas for further research which were not explored during this study.

8.2 RCA Concrete Database and Pilot Study

From the results of the pilot study involving the structural design and estimation of the carbon emissions of a high-rise reinforced concrete building frame, it was observed that RCA concrete, depending on the quality of the material, can reduce the building's overall environmental impact. Using lower quality RCA sourced from CDW, the reduced concrete compressive strength resulted in inferior environmental benefits because of the increase in volume of the materials (i.e., concrete and reinforcing steel) in the structure. Using higher quality RCA (with similar compressive strengths as conventional concrete) resulted in significantly lower total eCO_2 compared to the control structure. This pilot study also informed the following phases of the research with respect to:

- The inclusion of scenarios in which RCA concrete can be used selectively in specific structural elements within a building to potentially yield reduced eCO_2 emissions.
- The use of different structural floor systems for the study structure with both flat-plate and flat-slab design scenarios.

- As the structural design process used in this initial study was simplified, further investigation into the use of different design practices needed to be evaluated in subsequent research phases.

The pilot study conducted also highlighted the need for a database of concrete mixes with information of the mix compositions and strength reductions due to RCA use. A total of 145 conventional and RCA concrete mixes obtained from the literature were included in the database.

8.3 RCA Concrete Structure eCO_2 Emission Analysis

In the next phase of the study, by analysing the carbon emissions of each of the 80 design scenarios considered, multiple observations were made on the use of RCA in reinforced concrete structures:

1. The eCO_2 emissions associated with RCA concrete depends mainly on the quality of the aggregate that is available for construction. As the source, contents, and availability of the RCA are significant factors, the best approach to benefiting from the eCO_2 reduction needs to be considered on a case-by-case or project-by-projected.
2. The results of the structural design showed that the lower quality RCA produces concrete with lower compressive strength required a corresponding increase in member dimensions and/or reinforcing steel quantities, and therefore, a corresponding increase in eCO_2. However, with reduced transportation requirements for RCA that can be sourced closer to the construction site, even with lower compressive strengths, a minor reduction in eCO_2 emissions can be achieved. For example, in a scenario where natural aggregates would

need to be transported 100 km while lower quality RCA is available within 10 km, reductions in eCO_2 of up to 8% can be obtained.

3. The type of the structural floor system is also an important factor in determining the overall emissions of an RCA concrete building. For high quality RCA using a flat-slab structure instead of flat-plate resulted in a lesser reduction of eCO_2 emissions. In contrast, with low quality RCA, the reduction in eCO_2 emissions increased from 3% to 4% with the introduction of drop panels to the structure. This demonstrates that when high quality RCA is not available for a construction project, designers may investigate avoiding a flat-plate design to maximize the eCO_2 emissions reduction.
4. Another design scenario analysed the selective use of RCA concrete throughout the building to preserve the compressive strength of members whose design are more highly influenced by concrete compressive strength such as columns and core walls. In comparison to designs which incorporating RCA concrete in all elements, the selective use of RCA concrete resulted in the lowest reduction in eCO_2 emissions for the high-quality RCA at 10.3%. However, it also resulted in the highest reduction in eCO_2 emissions for the lower-quality RCA at 4.3%. This shows that considering a building design which selectively uses of RCA concrete in certain structural elements (i.e., slabs, etc.) can be helpful in reducing the emissions of the project when using low quality RCA. As the lower strength concrete makes up majority of structural elements by volume the emission reduction from RCA use is maximised and the lower strength does not have a significant effect compared to full RCA. Specifying material changes has the advantage of being easier to implement (i.e., compared to changing the floor system) as there is no constraint on the type of structural system that can be used.

5. The last set of design scenarios examined a structure designed with a flat-slab floor system with the selective use of RCA concrete. The results did not demonstrate any improvement for high quality RCA, but for lower quality RCA this combination had the highest eCO_2 emission reduction out of all design scenarios of 8%. In a construction project where the type of floor system is not constrained, and only lower quality RCA is available, this would be the best case for maximising the sustainability of the design.

8.4 Evaluating Trade-Offs Between Total eCO_2 and Cost

The final phase of this research focused on the estimation of construction costs when using RCA concrete and evaluating the relationships and trade-offs between the cost of a project and its total associated eCO_2 emissions. After estimating the costs for every design scenario, these were compared with the corresponding eCO_2 emissions. Based on this comparison and subsequent analysis, several significant conclusions were made,

1. The type of floor system utilised was more significant compared to the use of material when estimating the overall cost of the structure. As a result of the added labour costs associated with flat-slab compared to flat-plate structures (e.g., additional concrete forming and placing at drop panels) the overall cost of construction for these designs were higher. However, when calculating the eCO_2 emissions, the individual materials (cement/steel/aggregates) contributed more significantly, resulting in a reduction in emissions when using flat-slab designs with lower quality RCA. This demonstrates that to reduce eCO_2 emissions when using lower quality RCA, there will be an increase to the cost of the structure unless there are significant constraints for natural aggregate availability to offset the higher labour costs.

2. Considering the varying quality of RCA, it was observed that there may be changes to the cost of the material used. Lower quality RCA may potentially be cheaper than the natural alternative, while high quality RCA from specific sources or after undergoing pre-treatments can have a higher cost. With no reliable method of judging the changes to the cost of different types of RCA with respect to the scope of the study, an uncertainty of 1-1.2% was derived when calculating the cost of construction from RCA cost data. This uncertainty was calculated based on the lowest and highest RCA costs found in the literature and the overall effect on the construction costs.
3. The material transportation distance was also found to have a less significant impact on the overall cost of construction compared to its contribution to overall eCO_2 emissions. For example, for the worst case scenario of a coarse aggregate needing to be transported from a quarry 100 km away from the site, the cost of the structure was computed to only increase by up to 3%.
4. When comparing the costs and the emissions for each of the design scenarios analyzed, the combined lowest building cost and lowest eCO_2 footprint for high- and median-quality RCA were associated with flat-plate structures which utilized RCA concrete in selective (i.e., low strength structural elements such as slabs). The lowest eCO_2 emission for low-quality RCA is found in the flat-slab partial RCA concrete design and results in an increase to construction cost.

8.5 Overall Conclusions and Recommendations

In this study, an RCA concrete database was created using information about mix properties and compressive strength performance obtained from over 145 concrete mixes from published studies. This database was used to determine the different levels of compressive strength reduction that can result from the use of RCA. With the mix proportions obtained and additional information on the eCO_2 emissions of each constituent, the emissions of each mix were also calculated. A reinforced concrete frame structure was designed using the concrete mixes at different levels of compressive strength. For each strength level four potential designs were considered with flat-slab or flat-plate floor systems, and RCA concrete present in all or only low strength members. For each structure four construction scenarios were considered with different transportation requirements for the aggregates used. With the eCO_2 emissions of materials determined, emissions were calculated for each scenario structure. Additionally, the cost of construction was also estimated for each of the scenarios considered.

From the development and execution of the various outlined research stages and the analysis and comparison of the results produced, several overarching conclusions can be drawn:

1. When planning to utilise RCA concrete in new construction, the quality of the material available is the main factor in determining overall project feasibility, the degree of reduction in eCO_2 emissions and cost implications. With high quality RCA obtained either from carefully selected sources or derived using special aggregate pre-treatment methods, this study revealed that these high-quality RCA concrete structures always resulted in designs with lower eCO_2 compared to the control structure utilizing conventional concrete. Additionally, in most cases, the overall construction cost was either lower or similar to the conventional concrete structure.
2. The second most important factor when estimating the eCO_2 emissions associated with using RCA concrete, was the transportation distance from the site to the source of the aggregates. When considering long transportation distances when using natural aggregates (which seems to be becoming a more common scenario), the RCA concrete structures

analysed resulted in overall lower eCO_2 emissions in comparison even when using low quality RCA. However, transportation distances were observed to affect the overall eCO_2 footprint disproportionately compared to the overall structure costs as RCA quality had a much more significant effect on construction cost.

3. As the quality of RCA that is available in a construction project is the main factor for the performance of the material, the availability of performance data on local sources of RCA is scarce. In this study, the compressive strength reductions for RCA concrete were estimated at different levels based on a comprehensive review and analysis of the research literature. If RCA concrete is to be used for construction projects in the future, engineers will need more information on their strength properties and locations of aggregate sources. This could be obtained through a preliminary investigation of available aggregate sources with compressive strength testing before the structural design process. Testing could also potentially take place for each RCA source and be made available to promote the use of CDW for new construction.

8.6 Areas for Future Research

Over the course of this study, there were multiple areas of research that were not explored, due mainly to time constraints. Nevertheless, these unexplored areas of research could potentially present important findings and therefore should be considered for future research:

1. Although in this study the eCO_2 emissions of each scenario were used as the primary indicator of sustainability, in real world projects this is not necessarily the case. The Lifecycle Assessment process includes several impact categories aside from eCO_2 emissions such as the ozone depletion and non-renewable resource consumption. By

undertaking a more targeted study which considers these new impact categories, the overall sustainability of RCA concrete could be better understood.

2. As the use of 100% replacement of natural aggregate with RCA is not supported in most design codes and standards, the impact of this substitution needs to be further examined. Although in this study the main differences in structural design were due to the reduction in compressive strength, there can also be impacts on the overall structure stiffness and durability properties when using RCA concrete. Determining changes to the service life of the structure and the maintenance requirements could also result in additional emissions over the complete lifecycle of the project.
3. Investigating the use of RCA concrete in structures of different types and capacities would also be an interesting area of research in the future. This study analyzed a typical 21-storey structure with varying designs, concrete mixes, and material transportation scenarios. It would be interesting to see the effects of RCA concrete use in low-rise structures and in more rural areas where compressive strength would be less significant but high-quality RCA could also be more difficult to source.

REFERENCES

American Concrete Institute (2019). Building Code Requirements for Structural Concrete (ACI 318-19)

Alnahhal, M. F., Alengaram, U. J., Jumaat, M. Z., Abutaha, F., Alqedra, M. A., & Nayaka, R. R. (2018). Assessment on engineering properties and CO2 emissions of recycled aggregate concrete incorporating waste products as supplements to Portland cement. Journal of Cleaner Production, 203, 822–835.

Abid, S. R., Nahhab, A. H., Al-aayedi, H. K. H., & Nuhair, A. M. (2018). Expansion and strength properties of concrete containing contaminated recycled concrete aggregate. Case Studies in Construction Materials, 9, e00201. https://doi.org/10.1016/j.cscm.2018.e00201

Ahmad Bhat, J. (2021). Effect of strength of parent concrete on the mechanical properties of recycled aggregate concrete. Materials Today: Proceedings, 42, 1462–1469. https://doi.org/10.1016/j.matpr.2021.01.310

Alan D. Buck. (1976). Recycled Concrete Aggregate As a Source of Aggregate. U.S. Army Engineer Waterways Experiment Station Concrete Laboratory

Australian Road Research Board (ARRB). (2009). Recycled Aggregates Bring Carbon Reduction Benefits. www.sustainableaggregates.com.au.

Baccini, P. (1997). A city’s metabolism: Towards the sustainable development of urban systems. Journal of Urban Technology, 4(2), 27–39.

Bai, W., Li, W., Guan, J., Wang, J., & Yuan, C. (2020). Research on the mechanical properties of recycled aggregate concrete under uniaxial compression based on the statistical damage model. Materials, 13(17). https://doi.org/10.3390/MA13173765

Beatriz da Silva, J., Pepe, M., & Toledo Filho, R. D. (2020). High temperatures effect on mechanical and physical performance of normal and high strength recycled aggregate concrete. Fire Safety Journal, 117, 103222. doi:10.1016/j.firesaf.2020.103222

Butler, L. J., West, J. S., & Tighe, S. L. (2014). Towards the classification of recycled concrete aggregates: influence of fundamental aggregate properties on recycled concrete performance. Journal of Sustainable Cement-Based Materials, 3(2), 140–163.

Butler, L., West, J. S., & Tighe, S. L. (2011). The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement. Cement and Concrete Research, 41(10), 1037–1049.

C. Thomas, J. de Brito, V. Gil, J.A. Sainz-Aja, A. Cimentada, Multiple recycled aggregate properties analysed by X-ray microtomography, Constr. Build. Mater. 166 (2018) 171–180. https://doi.org/10.1016/j.conbuildmat.2018.01.130.

Capitol Aggregates Inc. (2015). A cradle-to-gate EPD of five cement products according to ISO 14025 and ISO 21930

Chinzorigt, G., Lim, M. K., Yu, M., Lee, H., Enkbold, O., & Choi, D. (2020). Strength, shrinkage and creep and durability aspects of concrete including CO2 treated recycled fine aggregate. Cement and Concrete Research, 136(January), 106062.

City of Winnipeg. (2012). South End Plant Process Selection Report.

Commercial Metals Company. (2016). Environmental Product Declaration

Concrete Reinforcing Steel Institute. (2017). Environmental Product Declaration

CSA A23.1-09/a23.2-09. (2009). Concrete materials and methods of concrete construction/Test methods and standard practices for concrete. In Canadian standards association.

D. Pedro, J. de Brito, L. Evangelista, Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: Mechanical, durability and long-term properties, Constr. Build. Mater. 154 (2017) 294–309. https://doi.org/10.1016/j.conbuildmat.2017.07.215.

Ding, T., Xiao, J., & Tam, V. W. Y. (2016). A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. Waste Management, 56, 367–375.

Duan, Z. H., & Poon, C. S. (2014). Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars. Materials and Design, 58, 19–29. https://doi.org/10.1016/j.matdes.2014.01.044

ECRA. (2015). Closing the loop: What type of concrete re-use is the most sustainable option? European Cement Research Academy, 41. www.ecra-online.org

Eleftheriadis, S., Duffour, P., Greening, P., James, J., Stephenson, B., & Mumovic, D. (2018). Investigating relationships between cost and CO2 emissions in reinforced concrete structures using a BIM-based design optimisation approach. Energy and Buildings, 166, 330–346.

Etc/Scp. (2009). EU as a Recycling Society. Present recycling levels of Municipal Waste and Construction & Demolition Waste in the EU. European Topic Centre on Resource and Waste Management, April, 1–73. http://scp.eionet.europa.eu/publications/wp2009_2/wp/WP2009_2

European Commission (2017). Internal Market, Industry, Entrepreneurship and SMEs. Retrieved from https://ec.europa.eu/growth/sectors/construction_en.

Evangelista, L., & de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cement and Concrete Composites, 29(5), 397–401.

Fahmy, M. F. M., & Idriss, L. K. (2019). Flexural behaviour of large scale semi-precast reinforced concrete T-beams made of natural and recycled aggregate concrete. Engineering Structures, 198(August), 109525.

Fantilli, A. P., Mancinelli, O., & Chiaia, B. (2019). The carbon footprint of normal and high-strength concrete used in low-rise and high-rise buildings. Case Studies in Construction Materials, 11, e00296.

Flower, D. J. M., & Sanjayan, J. G. (2007). Greenhouse gas emissions due to concrete manufacture. The International Journal of Life Cycle Assessment, 12(5), 282–288.

Gartner, E. (2004). Industrially interesting approaches to “low-CO 2” cements. Cement and Concrete Research, 34(9), 1489–1498.

Global Cement and Concrete Association. (2021). Global Cement and Concrete Industry Announces Roadmap To Achieve Ground-breaking ‘Net Zero’ Co2 Emissions By 2050. https://gccassociation.org

Golder Associates Ltd. (2009). Supply and Demand Study of Aggregate Resources Supplying the Greater Golden Horseshoe

Gursel, A. P., & Ostertag, C. (2019). Life-Cycle Assessment of High-Strength Concrete Mixtures with Copper Slag as Sand Replacement. Advances in Civil Engineering, 2019. https://doi.org/10.1155/2019/6815348

Hanif, A. (2020). Influence of the pre-treatment of recycled aggregates. In Advances in Construction and Demolition Waste Recycling. Elsevier Ltd. https://doi.org/10.1016/b978-0-12-819055-5.00009-7

Hasanbeigi, A., Arens, M., Cardenas, J. C. R., Price, L., & Triolo, R. (2016). Comparison of carbon dioxide emissions intensity of steel production in China, Germany, Mexico, and the United States. Resources, Conservation and Recycling, 113, 127–139.

He, Z., Zhu, X., Wang, J., Mu, M., & Wang, Y. (2019). Comparison of CO 2 emissions from OPC and recycled cement production. Construction and Building Materials, 211, 965–973.

Ho, N. Y., Lee, Y. P. K., Lim, W. F., Chew, K. C., Low, G. L., & Ting, S. K. (2015). Evaluation of RCA concrete for the construction of Samwoh Eco-Green Building. Magazine of Concrete Research, 67(12), 633–644. https://doi.org/10.1680/macr.14.00212

Hossaini, N., Reza, B., Akhtar, S., Sadiq, R., & Hewage, K. (2015). AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver. Journal of Environmental Planning and Management, 58(7), 1217–1241.

Icdas. (2015). Environmental Product Declaration for Carbon Steel Reinforcing Bar

ISO/TC 71, (2005). Business Plan. Concrete, Reinforced Concrete and Prestressed Concrete. International Organization for Standardization

J. García-González, D. Rodríguez-Robles, A. Juan-Valdés, J.M. Morán-del Pozo, M.I. Guerra-Romero, Porosity and pore size distribution in recycled concrete, Mag. Concr. Res. 67 (2015) 1214–1221. https://doi.org/10.1680/jmacr.14.00218.

J. Xiao, J. Li, C. Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, Cem. Concr. Res. 35 (2005) 1187–1194. https://doi.org/10.1016/j.cemconres.2004.09.020.

Jiménez, L. F., Domínguez, J. A., & Vega-Azamar, R. E. (2018). Carbon footprint of recycled aggregate concrete. Advances in Civil Engineering, 2018. https://doi.org/10.1155/2018/7949741

Kangley Rock & Recycling. (2018). Environmental Product Declaration

Katz, A. (2003) Properties of Concrete Made with Recycled Aggregate from Partially Hydrated Old Concrete. Cement and Concrete Research, 33, 703-711. http://dx.doi.org/10.1016/S0008-8846(02)01033-5.

Knoeri, C., Sanye-Mengual, E., Althaus, H.J., 2013. Comparative LCA of recycled and conventional concrete for structural applications. Int. J. Life Cycle Assess. 18, 909-918.

M. Alhawat, A. Ashour, Bond strength between corroded steel reinforcement and recycled aggregate concrete, Structures. 19 (2019) 369–385. https://doi.org/10.1016/j.istruc.2019.02.001.

Martin Marietta. (2017). Environmental Product Declaration

Meng, D., Wu, X., Quan, H., & Zhu, C. (2021). A strength-based mix design method for recycled aggregate concrete and consequent durability performance. Construction and Building Materials, 281, 122616. https://doi.org/10.1016/j.conbuildmat.2021.122616

Mi, R., Pan, G., Liew, K. M., & Kuang, T. (2020). Utilizing recycled aggregate concrete in sustainable construction for a required compressive strength ratio. Journal of Cleaner Production, 124249. doi:10.1016/j.jclepro.2020.124249

Olcun, S., Santorsola, J., Butler, L. J. (2021). Design and Trade-off Optimization for Reduction of Carbon Emissions in Concrete Structures Using Recycled Materials. fib Symposium 2021.

Ontario, M. of N. R. (2010). State of the Aggregate Resource in Ontario Study (Issue February). http://files.ontario.ca/environment-and-energy/aggregates/aggregate-resource-in-ontario-study/286996.pdf

Ouyang, K., Liu, J., Liu, S., Song, B., Guo, H., Li, G., & Shi, C. (2023). Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: A review. Resources, Conservation and Recycling, 188(April 2022), 106717. https://doi.org/10.1016/j.resconrec.2022.106717

Park, W. J., Kim, T., Roh, S., & Kim, R. (2019). Analysis of life cycle environmental impact of recycled aggregate. Applied Sciences (Switzerland), 9(5).

Polaris Materials. (2017). Environmental Product Declaration

Portland Cement Association. (2016). Environmental Product Declaration

Pradhan, S., Tiwari, B. R., Kumar, S., & Barai, S. V. (2019). Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix. Journal of Cleaner Production, 228, 679–691.

Purnell, P. (2013). The carbon footprint of reinforced concrete. Advances in Cement Research, 25(6), 362–368. https://doi.org/10.1680/adcr.13.00013

R.K. Majhi, A.N. Nayak, Bond, durability and microstructural characteristics of ground granulated blast furnace slag based recycled aggregate concrete, Constr. Build. Mater. 212 (2019) 578–595. https://doi.org/10.1016/j.conbuildmat.2019.04.017.

Robu, I., Mazilu, C., & Deju, R. (2017). Study Concerning Characterization of Some Recycled Concrete Aggregates Ion. Mathematical Modelling in Civil Engineering, 13(3), 10–20.

Raut, S., Olcun, S., Butler, L. J. (2022). Evaluating the use of limestone calcined clay cement and recycled concrete aggregates for reducing the carbon footprint of concrete structures. Construction Materials and Structures, ICCMS-2022

S.C. Kou, C.S. Poon, M. Etxeberria, Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete, Cem. Concr. Compos. 33 (2011) 286–291. https://doi.org/10.1016/j.cemconcomp.2010.10.003.

Samad, S., & Shah, A. (2017). Role of binary cement including Supplementary Cementitious Material (SCM), in production of environmentally sustainable concrete: A critical review. International Journal of Sustainable Built Environment, 6(2), 663–674.

Santorsola, J. A. (2021). Development and Structural Performance Assessment of Low-Carbon Concrete Using Recycled Concrete Aggregates and Secondary Materials. York University Thesis. http://hdl.handle.net/10315/39101

Sherwood Steel LTD. (2017). Environmental Product Declaration

Statistics Canada. 2012. “Canada Yearbook, 2012” Accessed January 2021.

Tabsh, S. W., & Abdelfatah, A. S. (2009). Influence of recycled concrete aggregates on strength properties of concrete. Construction and Building Materials, 23(2), 1163–1167. https://doi.org/10.1016/j.conbuildmat.2008.06.007

Tošić, N., Torrenti, J. M., Sedran, T., & Ignjatović, I. (2020). Toward a codified design of recycled aggregate concrete structures: Background for the new fib Model Code 2020 and Eurocode 2. Structural Concrete, August 1–23.

U.S. Environmental Protection Agency. (2006). Life Cycle Assessment: Principles and Practice.

Visintin, P., Xie, T., & Bennett, B. (2020). A large-scale life-cycle assessment of recycled aggregate concrete: The influence of functional unit, emissions allocation, and carbon dioxide uptake. Journal of Cleaner Production, 248, 119243.

Vulcan Materials. (2016). Environmental Product Declaration

W. Dodds, C. Christodoulou, C. Goodier, S. Austin, D. Dunne, Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on rapid chloride migration and accelerated corrosion, Constr. Build. Mater. 155 (2017) 511–521. https://doi.org/10.1016/j.conbuildmat.2017.08.073.

W.C. Choi, H. Do Yun, Compressive behavior of reinforced concrete columns with recycled aggregate under uniaxial loading, Eng. Struct. 41 (2012) 285–293. https://doi.org/10.1016/j.engstruct.2012.03.037.

Xiao, J., Huang, X., & Shen, L. (2012). Seismic behaviour of semi-precast column with recycled aggregate concrete. Construction and Building Materials, 35, 988–1001.

Xiao, J., Wang, C., Ding, T., & Akbarnezhad, A. (2018). A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint. Journal of Cleaner Production, 199, 868–881.

Y. Kim, A. Hanif, M. Usman, W. Park, Influence of bonded mortar of recycled concrete aggregates on interfacial characteristics – Porosity assessment based on pore segmentation from backscattered electron image analysis, Constr. Build. Mater. 212 (2019) 149–163. https://doi.org/10.1016/j.conbuildmat.2019.03.265.

Yoon, Y. C., Kim, K. H., Lee, S. H., & Yeo, D. (2018). Sustainable design for reinforced concrete columns through embodied energy and CO2 emission optimization. Energy and Buildings, 174, 44–53.

Z. Chen, J. Xu, J. Xue, Y. Su, Performance and calculations of recycled aggregate concrete-filled steel tubular (RACFST) short columns under axial compression, Int. J. Steel Struct. 14 (2014) 31–42. https://doi.org/10.1007/s13296-014-1005-5.

Z. Guo, C. Chen, D.E. Lehman, W. Xiao, S. Zheng, B. Fan, Mechanical and durability behaviours of concrete made with recycled coarse and fine aggregates, Eur. J. Environ. Civ. Eng. 8189 (2017) 1–19. https://doi.org/10.1080/19648189.2017.1371083.

Zareei, S. A., Ameri, F., Dorostkar, F., & Ahmadi, M. (2017). Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. Case Studies in Construction Materials, 7(May), 73–81.

Zhang, C. Y., Han, R., Yu, B., & Wei, Y. M. (2018). Accounting process-related CO2 emissions from global cement production under Shared Socioeconomic Pathways. Journal of Cleaner Production, 184, 451–465.

Zhu, C., Liu, C., Bai, G., & Fan, J. (2020). Study on long-term performance and flexural stiffness of recycled aggregate concrete beams. Construction and Building Materials, 262, 120503. doi:10.1016/j.conbuildmat.2020.120503

APPENDICES

Appendix A RCA Concrete Strength and Emission Database

This section presents the database of NA and RCA concrete mixes constructed for the study, each mix is included with the corresponding mix proportions, target strengths, actual strengths, eCO_2 emissions, and sources they were obtained from.

Table A. 1: RCA Concrete Strength and Emission Database

Aggregate Type	**Cement (kg)**	**Water (kg)**	**w/c**	**NCA (kg)**	**RCA (kg)**	**NFA (kg)**	**Target Strength (MPa)**	**Actual Strength (MPa)**	**Strength Reduction**	**Production Emissions (kg eCO_2)**	**Reference**
NA	364.0	182.0	0.50	909.0	0.0	818.0	30	37.9	0.00%	335.10	Chinzorigt et al., 2020
RCA	364.0	182.0	0.50	0.0	821.0	818.0	30	33.8	10.82%	334.63	Chinzorigt et al., 2020
NA	305.2	200.8	0.66	1035.3	0.0	752.4	30	34.19	0.00%	282.53	Santorsola, 2021
NA	507.1	234.4	0.46	1035.3	0.0	505.0	50	56.77	0.00%	463.38	Santorsola, 2021
RCA	305.2	209.8	0.69	0.0	935.4	751.0	30	28.75	15.91%	282.00	Santorsola, 2021
RCA	507.1	242.9	0.48	0.0	935.4	504.1	50	33.43	41.11%	462.85	Santorsola, 2021
NA	267.0	160.0	0.60	1106.0	0.0	861.0	30	32.1	0.00%	248.73	Butler et al., 2014
NA	474.0	180.0	0.38	1106.0	0.0	633.0	50	57.3	0.00%	434.14	Butler et al., 2014

Aggregate Type	**Cement (kg)**	**Water (kg)**	**w/c**	**NCA (kg)**	**RCA (kg)**	**NFA (kg)**	**Target Strength (MPa)**	**Actual Strength (MPa)**	**Strength Reduction**	**Production Emissions (kg eCO$_2$)**	**Reference**
RCA	267.0	160.0	0.60	0.0	975.0	863.0	30	44.1	0.00%	248.09	Butler et al., 2014
RCA	474.0	180.0	0.38	0.0	975.0	635.0	50	59	0.00%	433.50	Butler et al., 2014
RCA	267.0	160.0	0.60	0.0	949.0	863.0	30	38.3	0.00%	248.01	Butler et al., 2014
RCA	474.0	180.0	0.38	0.0	949.0	635.0	50	54	5.76%	433.42	Butler et al., 2014
NA	364.0	193.0	0.53	1092.0	0.0	728.0	N/A	38.3	0.00%	335.51	Mi et al., 2020
RCA	364.0	193.0	0.53	0.0	1092.0	728.0	N/A	35.6	7.05%	335.28	Mi et al., 2020
RCA	364.0	193.0	0.53	0.0	1092.0	728.0	N/A	42.9	0.00%	335.28	Mi et al., 2020
RCA	364.0	193.0	0.53	0.0	1092.0	728.0	N/A	45	0.00%	335.28	Mi et al., 2020
NA	300.0	200.0	0.67	941.9	0.0	798.4	25	25.5	0.00%	277.68	Beatriz da Silva et al., 2020
RCA	268.2	172.9	0.64	0.0	941.8	829.3	25	28	0.00%	248.99	Beatriz da Silva et al., 2020
NA	500.0	170.0	0.34	895.2	0.0	758.8	65	65.2	0.00%	457.07	Beatriz da Silva et al., 2020
RCA	550.0	150.0	0.27	0.0	858.4	755.8	65	67.4	0.00%	501.67	Beatriz da Silva et al., 2020
NA	380.0	175.0	0.46	1232.0	0.0	633.0	30	34	0.00%	350.13	Zhu et al., 2020
RCA	380.0	175.0	0.46	0.0	1031.0	633.0	30	31.7	6.76%	349.24	Zhu et al., 2020
NA	310.0	198.0	0.64	1167.0	0.0	772.0	20	22.5	0.00%	287.35	Ahmad Bhat, 2021
NA	397.0	173.0	0.44	1186.0	0.0	671.0	40	43.5	0.00%	365.33	Ahmad Bhat, 2021

Aggregate Type	**Cement (kg)**	**Water (kg)**	**w/c**	**NCA (kg)**	**RCA (kg)**	**NFA (kg)**	**Target Strength (MPa)**	**Actual Strength (MPa)**	**Strength Reduction**	**Production Emissions (kg eCO$_2$)**	**Reference**
NA	450.0	170.0	0.38	1183.0	0.0	625.0	60	60	0.00%	412.82	Ahmad Bhat, 2021
RCA	310.0	198.0	0.64	0.0	1167.0	772.0	20	17.5	22.22%	287.11	Ahmad Bhat, 2021
RCA	310.0	198.0	0.64	0.0	1167.0	772.0	20	18.3	18.67%	287.11	Ahmad Bhat, 2021
RCA	310.0	198.0	0.64	0.0	1167.0	772.0	20	19.5	13.33%	287.11	Ahmad Bhat, 2021
RCA	397.0	173.0	0.44	0.0	1186.0	671.0	40	34.5	20.69%	365.08	Ahmad Bhat, 2021
RCA	397.0	173.0	0.44	0.0	1186.0	671.0	40	35	19.54%	365.08	Ahmad Bhat, 2021
RCA	397.0	173.0	0.44	0.0	1186.0	671.0	40	37.5	13.79%	365.08	Ahmad Bhat, 2021
RCA	450.0	170.0	0.38	0.0	1183.0	625.0	60	44.5	25.83%	412.57	Ahmad Bhat, 2021
RCA	450.0	170.0	0.38	0.0	1183.0	625.0	60	45	25.00%	412.57	Ahmad Bhat, 2021
RCA	450.0	170.0	0.38	0.0	1183.0	625.0	60	47	21.67%	412.57	Ahmad Bhat, 2021
NA	300.0	150.1	0.50	1257.0	0.0	677.0	N/A	43.7	0.00%	278.46	Meng et al., 2021
RCA	300.0	165.7	0.55	0.0	1206.0	677.0	N/A	33.9	22.43%	278.04	Meng et al., 2021
NA	350.0	146.7	0.42	1257.0	0.0	677.0	N/A	48.2	0.00%	323.37	Meng et al., 2021
RCA	350.0	165.1	0.47	0.0	1206.0	677.0	N/A	39.1	18.88%	322.94	Meng et al., 2021
NA	400.0	147.1	0.37	1257.0	0.0	677.0	N/A	52.8	0.00%	368.28	Meng et al., 2021
RCA	400.0	163.8	0.41	0.0	1206.0	677.0	N/A	43.5	17.61%	367.85	Meng et al., 2021
NA	450.0	147.1	0.33	1257.0	0.0	677.0	N/A	58.8	0.00%	413.18	Meng et al., 2021

Aggregate Type	**Cement (kg)**	**Water (kg)**	**w/c**	**NCA (kg)**	**RCA (kg)**	**NFA (kg)**	**Target Strength (MPa)**	**Actual Strength (MPa)**	**Strength Reduction**	**Production Emissions (kg eCO$_2$)**	**Reference**
RCA	450.0	164.8	0.37	0.0	1206.0	677.0	N/A	49.1	16.50%	412.76	Meng et al., 2021
NA	500.0	149.7	0.30	1257.0	0.0	677.0	N/A	64.8	0.00%	458.09	Meng et al., 2021
RCA	500.0	165.9	0.33	0.0	1206.0	677.0	N/A	53.4	17.59%	457.67	Meng et al., 2021
NA	304.5	177.4	0.58	973.9	0.0	913.6	30	36	0.00%	282.13	Tabsh and Abdelfatah, 2009
RCA	304.5	177.4	0.58	0.0	973.9	913.6	30	35.75	0.69%	281.92	Tabsh and Abdelfatah, 2009
RCA	304.5	177.4	0.58	0.0	973.9	913.6	30	25	30.56%	281.92	Tabsh and Abdelfatah, 2009
RCA	304.5	177.4	0.58	0.0	973.9	913.6	30	23	36.11%	281.92	Tabsh and Abdelfatah, 2009
NA	495.2	183.5	0.37	1007.7	0.0	706.4	50	52.5	0.00%	453.00	Tabsh and Abdelfatah, 2009
RCA	495.2	183.5	0.37	0.0	1007.7	706.4	50	50	4.76%	452.79	Tabsh and Abdelfatah, 2009
RCA	495.2	183.5	0.37	0.0	1007.7	706.4	50	47	10.48%	452.79	Tabsh and Abdelfatah, 2009
RCA	495.2	183.5	0.37	0.0	1007.7	706.4	50	46	12.38%	452.79	Tabsh and Abdelfatah, 2009
NA	311.0	205.0	0.66	1149.0	0.0	735.0	N/A	23.03	0.00%	288.11	Bai et al., 2020
RCA	311.0	220.7	0.71	0.0	1149.0	735.0	N/A	25.02	0.00%	287.87	Bai et al., 2020
NA	418.0	205.0	0.49	1164.0	0.0	613.0	N/A	28.27	0.00%	383.99	Bai et al., 2020
RCA	418.0	221.0	0.53	0.0	1164.0	613.0	N/A	32.35	0.00%	383.74	Bai et al., 2020

Aggregate Type	**Cement (kg)**	**Water (kg)**	**w/c**	**NCA (kg)**	**RCA (kg)**	**NFA (kg)**	**Target Strength (MPa)**	**Actual Strength (MPa)**	**Strength Reduction**	**Production Emissions (kg eCO$_2$)**	**Reference**
NA	539.0	205.0	0.38	1143.0	0.0	563.0	N/A	41.69	0.00%	492.48	Bai et al., 2020
RCA	539.0	220.8	0.41	0.0	1143.0	563.0	N/A	48.02	0.00%	492.24	Bai et al., 2020
NA	380.0	210.0	0.55	980.0	0.0	790.0	25	29.8	0.00%	349.64	Abid et al., 2018
RCA	380.0	210.0	0.55	0.0	980.0	790.0	25	22	26.17%	349.44	Abid et al., 2018
NA	350.0	150.5	0.43	1027.0	0.0	859.0	N/A	58.08	0.00%	323.01	Pedro et al., 2017
RCA	350.0	153.8	0.44	0.0	943.0	859.0	N/A	54.96	5.37%	322.53	Pedro et al., 2017
RCA	350.0	154.7	0.44	0.0	985.0	859.0	N/A /	53.52	7.85%	322.66	Pedro et al., 2017
NA	385.6	156.4	0.41	1080.7	0.0	710.8	N/A	32.3	0.00%	354.83	Kim et al., 2019
RCA	385.6	156.6	0.41	0.0	1004.5	710.8	N/A	29.5	8.67%	354.37	Kim et al., 2019
NA	487.5	195.0	0.40	1167.9	0.0	549.6	N/A	30.68	0.00%	446.28	Guo et al., 2017
RCA	487.5	195.0	0.40	0.0	1167.9	549.6	N/A	20.832	32.10%	446.04	Guo et al., 2017
NA	390.0	195.0	0.50	1197.9	0.0	617.1	N/A	24.296	0.00%	358.96	Guo et al., 2017
RCA	390.0	195.0	0.50	0.0	1197.9	617.1	N/A	19.944	17.91%	358.71	Guo et al., 2017
NA	325.0	195.0	0.60	1203.2	0.0	676.8	N/A	20.592	0.00%	300.73	Guo et al., 2017
RCA	325.0	195.0	0.60	0.0	1203.2	676.8	N/A	16.688	18.96%	300.48	Guo et al., 2017
NA	450.0	180.0	0.40	1180.0	0.0	664.0	N/A	43.728	0.00%	412.90	Alhawat and Ashour, 2019
RCA	450.0	180.0	0.40	0.0	1180.0	664.0	N/A	37.664	13.87%	412.65	Alhawat and Ashour, 2019

Aggregate Type	Cement (kg)	Water (kg)	w/c	NCA (kg)	RCA (kg)	NFA (kg)	Target Strength (MPa)	Actual Strength (MPa)	Strength Reduction	Production Emissions (kg eCO_2)	Reference
NA	392.0	132.0	0.34	960.0	0.0	823.0	N/A	37.05	0.00%	360.43	Choi and Do Yun, 2012
RCA	392.0	132.0	0.34	0.0	888.0	823.0	N/A	29.17	21.27%	360.00	Choi and Do Yun, 2012
NA	494.0	163.0	0.33	968.0	0.0	675.0	N/A	36.78	0.00%	451.74	Choi and Do Yun, 2012
RCA	494.0	163.0	0.33	0.0	664.0	675.0	N/A	36.6	0.49%	450.58	Choi and Do Yun, 2012
NA	430.0	185.0	0.43	1295.0	0.0	555.0	N/A	28.72	0.00%	395.07	Xiao et al., 2005
RCA	430.0	185.0	0.43	0.0	1149.0	492.0	N/A	21.36	25.63%	394.20	Xiao et al., 2005
NA	390	195	0.50	1200	0	710	N/A	32	0.00%	359.18	Majhi and Nayak, 2019
RCA	390	195	0.50	0	1011	710	N/A	26.4	17.50%	358.34	Majhi and Nayak, 2019
NA	390	195	0.50	1162	0	653	N/A	46.4	0.00%	358.92	Dodds et al., 2017
RCA	390	195	0.50	0	1162	656	N/A	36	22.41%	358.69	Dodds et al., 2017
NA	294	161	0.55	1344	0	421	N/A	33.68	0.00%	272.78	Katz, 2003
RCA	293	160	0.55	0	1440	254	N/A	16.88	49.88%	271.53	Katz, 2003
RCA	302	165	0.55	0	1484	219	N/A	24.4	27.55%	279.67	Katz, 2003
RCA	296	162	0.55	0	1457	238	N/A	23.28	30.88%	274.24	Katz, 2003
NA	298	163	0.55	1361	0	427	N/A	27.68	0.00%	276.45	Katz, 2003
RCA	298	166	0.56	0	1453	259	N/A	21.28	23.12%	276.07	Katz, 2003
RCA	300	168	0.56	0	1460	217	N/A	20.64	25.43%	277.79	Katz, 2003
RCA	298	163	0.55	0	1456	240	N/A	21.44	22.54%	276.04	Katz, 2003

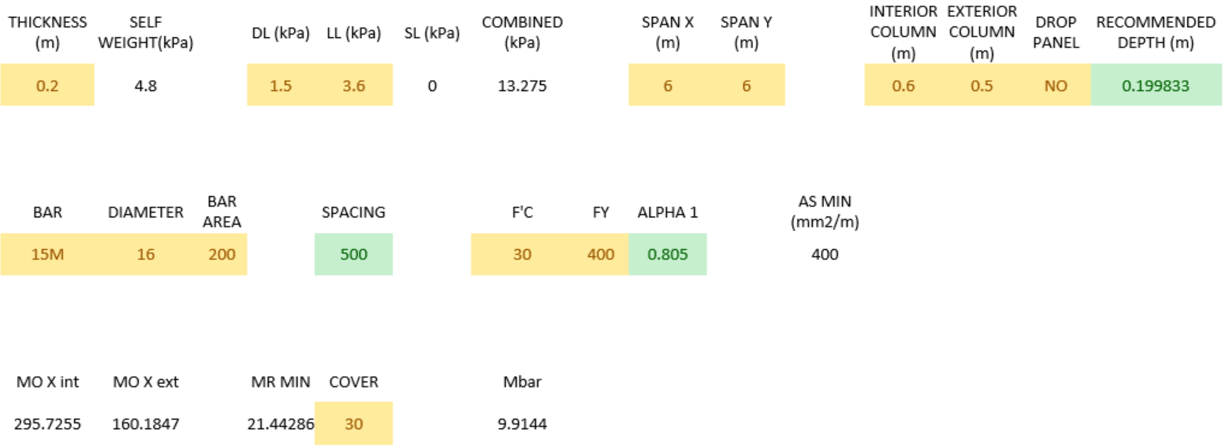
Aggregate Type	Cement (kg)	Water (kg)	w/c	NCA (kg)	RCA (kg)	NFA (kg)	Target Strength (MPa)	Actual Strength (MPa)	Strength Reduction	Production Emissions (kg eCO$_2$)	Reference
NA	390.91	215	0.55	1030.71	0	650.49	N/A	38.46	0.00%	359.30	García-González et al., 2015
RCA	390.91	215	0.55	0	769.28	762.56	N/A	31.13	19.06%	358.52	García-González et al., 2015
NA	355	195	0.55	1127	0	690	N/A	35.04	0.00%	327.45	Kou et al., 2011
RCA	355	195	0.55	0	1038	690	N/A	27.44	21.69%	326.94	Kou et al., 2011
RCA	355	195	0.55	0	1068	690	N/A	28.48	18.72%	327.03	Kou et al., 2011
NA	350	194	0.55	975	0	732	N/A	55.9	0.00%	322.55	Thomas et al., 2018
RCA	350	194	0.55	0	871	732	N/A	54.1	3.22%	322.02	Thomas et al., 2018
RCA	350	194	0.55	0	816	732	N/A	53.3	4.65%	321.85	Thomas et al., 2018
NA	524	215	0.41	1129	0	532	N/A	24.88	0.00%	478.90	Chen et al., 2014
RCA	524	215	0.41	0	1129	532	N/A	30.744	0.00%	478.66	Chen et al., 2014
NA	300	205	0.68	1128	0	697	N/A	27.6	0.00%	278.07	Duan and Poon, 2014
RCA	300	205	0.68	0	1075	697	N/A	28	0.00%	277.67	Duan and Poon, 2014
RCA	300	205	0.68	0	1027	697	N/A	23.36	15.36%	277.52	Duan and Poon, 2014
RCA	300	205	0.68	0	1027	697	N/A	22.16	19.71%	277.52	Duan and Poon, 2014
NA	350	180	0.51	1143	0	706	N/A	38.64	0.00%	323.05	Duan and Poon, 2014
RCA	350	180	0.51	0	1089	706	N/A	38.08	1.45%	322.64	Duan and Poon, 2014

Aggregate Type	**Cement (kg)**	**Water (kg)**	**w/c**	**NCA (kg)**	**RCA (kg)**	**NFA (kg)**	**Target Strength (MPa)**	**Actual Strength (MPa)**	**Strength Reduction**	**Production Emissions (kg eCO_2)**	**Reference**
RCA	350	180	0.51	0	1041	706	N/A	33.6	13.04%	322.49	Duan and Poon, 2014
RCA	350	180	0.51	0	7311	706	N/A	34.32	11.18%	342.06	Duan and Poon, 2014
NA	425	185	0.44	1077	0	696	N/A	49.28	0.00%	390.17	Duan and Poon, 2014
RCA	425	185	0.44	0	1028	696	N/A	48	2.60%	389.79	Duan and Poon, 2014
RCA	425	185	0.44	0	982	696	N/A	42.96	12.82%	389.65	Duan and Poon, 2014
RCA	425	185	0.44	0	985	696	N/A	42.56	13.64%	389.66	Duan and Poon, 2014
NA	485	165	0.34	1089	0	685	N/A	64.4	0.00%	444.08	Duan and Poon, 2014
RCA	485	165	0.34	0	1039	685	N/A	62.56	2.86%	443.69	Duan and Poon, 2014
RCA	485	165	0.34	0	979	685	N/A	56.96	11.55%	443.51	Duan and Poon, 2014
RCA	485	165	0.34	0	982	685	N/A	52.32	18.76%	443.51	Duan and Poon, 2014

Appendix B Sample Design Calculations

Appendix B provides examples of sample calculations performed for the design and material inventory of the hypothetical structures. The process used is explained in further detail in chapter 4 with some sample calculation provided in this section for the control structure specifically.

B.1 Initial Slab Depth Calculations



THICKNESS (m)	SELF WEIGHT(kPa)	DL (kPa)	LL (kPa)	SL (kPa)	COMBINED (kPa)	SPAN X (m)	SPAN Y (m)	INTERIOR COLUMN (m)	EXTERIOR COLUMN (m)	DROP PANEL	RECOMMENDED DEPTH (m)
0.2	4.8	1.5	3.6	0	13.275	6	6	0.6	0.5	NO	0.199833

BAR	DIAMETER	BAR AREA	SPACING	F'C	FY	ALPHA 1	AS MIN (mm2/m)
15M	16	200	500	30	400	0.805	400

MO X int	MO X ext	MR MIN	COVER	Mbar
295.7255	160.1847	21.44286	30	9.9144

Initial slab thickness, h_s, calculation in accordance with Clauses 13.2.3 and 13.2.4 from CSA A23.3-14:

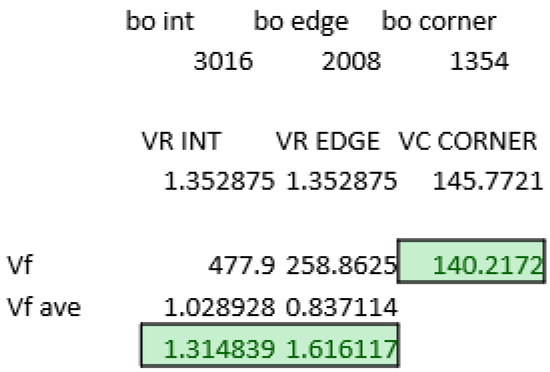
$$h_s \leq \frac{l_n(0.6 + \frac{f_y}{1000})}{30}$$

$$\text{RECOMMENDED DEPTH} \leq \frac{(\text{SPAN} - \text{INTERIOR COLUMN})(0.6 + \frac{\text{FY}}{1000})}{30} \qquad (4\text{-}7)$$

$$\text{RECOMMENDED DEPTH} \leq \frac{(6 - 0.6)\left(0.6 + \frac{400}{1000}\right)}{30}$$

$$\text{RECOMMENDED DEPTH} \leq 0.18$$

B.2 Punching Shear Check



	bo int	bo edge	bo corner
	3016	2008	1354
	VR INT	VR EDGE	VC CORNER
	1.352875	1.352875	145.7721
Vf	477.9	258.8625	140.2172
Vf ave	1.028928	0.837114	
	1.314839	1.616117	

Two-way (punching) shear calculation at the interior square columns as specified by Clause 13.3.4.1 from CSA A23.3-14:

$$V_r = V_c = \left(1 + \frac{2}{\beta_c}\right) 0.19 \lambda \phi_c \sqrt{f_c'}$$

$$V_r\ INT = \left(1 + \frac{2}{1}\right)(0.19)(1)(0.65)\sqrt{30} \tag{4-8}$$

$$V_r\ INT = 2.03$$

$$V_r = V_c = \left(\frac{\alpha_s d}{b_o} + 0.19\right) \lambda \phi_c \sqrt{f_c'}$$

$$V_r\ INT = \left(\frac{4 \times 211}{3016} + 0.19\right)(1)(0.65)\sqrt{30} \tag{4-9}$$

$$V_r\ INT = 1.67$$

$$V_r = V_c = 0.38\lambda\phi_c\sqrt{f_c'}$$

$$V_r\ INT = (0.38)(1)(0.65)\sqrt{30} \tag{4-10}$$

$$V_r\ INT = 1.35$$

USE MINIMUM $V_r\ INT = 1.35$

Following calculations of punching shear resistance, the factored shear is calculated with the applied dead and live loads to check for failure.

B.3 Slab Reinforcement Calculations

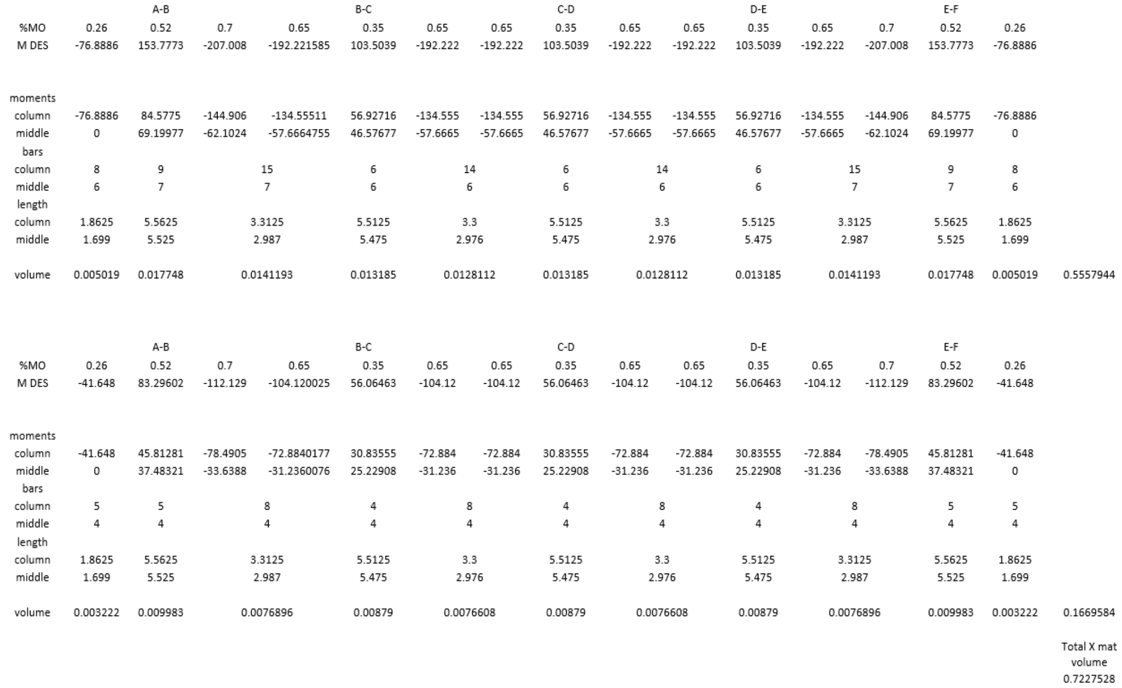
Sample moment calculation for interior span along x-axis:

$$M_o = \frac{w_f l_{2a} l_n^2}{8}$$

$$M_o = \frac{Distributed\ Dead\ and\ Live\ Load \times SPAN \times (SPAN - COLUMN)^2}{8} \tag{4-11}$$

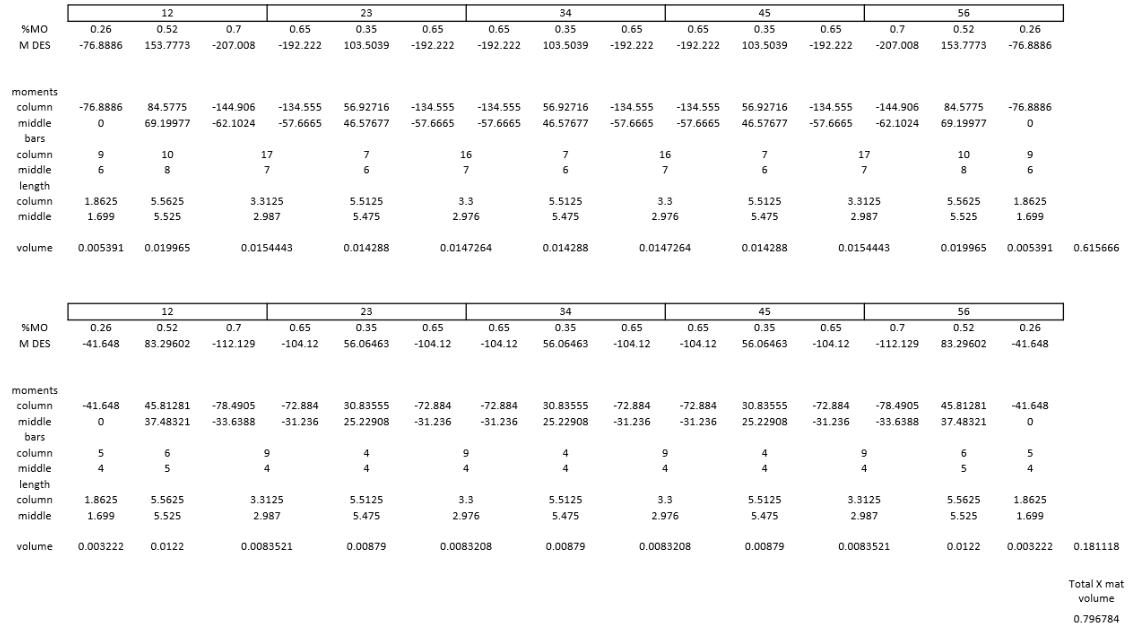
$$M_o = 266\ kNm$$

Design moments calculated and distributed, required reinforcement determined by design strips, and development length calculated for final volume calculation for slab top and bottom are shown in the following spreadsheet section. Each axis is calculated separately, labeled A-B-C… for North-South and 1-2-3… for East-West. Moments are calculated from factored load combinations and distributed along each span as discussed in Chapter 4. After considering the minimum reinforcement for the slab, the additional reinforcement requirements are calculated along the span and distributed to the column and middle strips. Reinforcement curtailment length is determined for each section and the total volume of steel is calculated.



		A-B			B-C			C-D			D-E			E-F		
%MO	0.26	0.52	0.7	0.65	0.35	0.65	0.65	0.35	0.65	0.65	0.35	0.65	0.7	0.52	0.26	
M DES	-76.8886	153.7773	-207.008	-192.221585	103.5039	-192.222	-192.222	103.5039	-192.222	-192.222	103.5039	-192.222	-207.008	153.7773	-76.8886	
moments																
column	-76.8886	84.5775	-144.906	-134.55511	56.92716	-134.555	-134.555	56.92716	-134.555	-134.555	56.92716	-134.555	-144.906	84.5775	-76.8886	
middle	0	69.19977	-62.1024	-57.6664755	46.57677	-57.6665	-57.6665	46.57677	-57.6665	-57.6665	46.57677	-57.6665	-62.1024	69.19977	0	
bars																
column	8	9	15		6	14		6	14		6	15		9	8	
middle	6	7	7		6	6		6	6		6	7		7	6	
length																
column	1.8625	5.5625	3.3125		5.5125	3.3		5.5125	3.3		5.5125	3.3125		5.5625	1.8625	
middle	1.699	5.525	2.987		5.475	2.976		5.475	2.976		5.475	2.987		5.525	1.699	
volume	0.005019	0.017748	0.0141193		0.013185	0.0128112		0.013185	0.0128112		0.013185	0.0141193		0.017748	0.005019	0.5557944

		A-B			B-C			C-D			D-E			E-F		
%MO	0.26	0.52	0.7	0.65	0.35	0.65	0.65	0.35	0.65	0.65	0.35	0.65	0.7	0.52	0.26	
M DES	-41.648	83.29602	-112.129	-104.120025	56.06463	-104.12	-104.12	56.06463	-104.12	-104.12	56.06463	-104.12	-112.129	83.29602	-41.648	
moments																
column	-41.648	45.81281	-78.4905	-72.8840177	30.83555	-72.884	-72.884	30.83555	-72.884	-72.884	30.83555	-72.884	-78.4905	45.81281	-41.648	
middle	0	37.48321	-33.6388	-31.2360076	25.22908	-31.236	-31.236	25.22908	-31.236	-31.236	25.22908	-31.236	-33.6388	37.48321	0	
bars																
column	5	5	8		4	8		4	8		4	8		5	5	
middle	4	4	4		4	4		4	4		4	4		4	4	
length																
column	1.8625	5.5625	3.3125		5.5125	3.3		5.5125	3.3		5.5125	3.3125		5.5625	1.8625	
middle	1.699	5.525	2.987		5.475	2.976		5.475	2.976		5.475	2.987		5.525	1.699	
volume	0.003222	0.009983	0.0076896		0.00879	0.0076608		0.00879	0.0076608		0.00879	0.0076896		0.009983	0.003222	0.1669584
																Total X mat volume 0.7227528



	12			23			34			45			56			
%MO	0.26	0.52	0.7	0.65	0.35	0.65	0.65	0.35	0.65	0.65	0.35	0.65	0.7	0.52	0.26	
M DES	-76.8886	153.7773	-207.008	-192.222	103.5039	-192.222	-192.222	103.5039	-192.222	-192.222	103.5039	-192.222	-207.008	153.7773	-76.8886	
moments																
column	-76.8886	84.5775	-144.906	-134.555	56.92716	-134.555	-134.555	56.92716	-134.555	-134.555	56.92716	-134.555	-144.906	84.5775	-76.8886	
middle	0	69.19977	-62.1024	-57.6665	46.57677	-57.6665	-57.6665	46.57677	-57.6665	-57.6665	46.57677	-57.6665	-62.1024	69.19977	0	
bars																
column	9	10	17		7	16		7	16		7	17		10	9	
middle	6	8	7		6	7		6	7		6	7		8	6	
length																
column	1.8625	5.5625	3.3125		5.5125	3.3		5.5125	3.3		5.5125	3.3125		5.5625	1.8625	
middle	1.699	5.525	2.987		5.475	2.976		5.475	2.976		5.475	2.987		5.525	1.699	
volume	0.005391	0.019965	0.0154443		0.014288	0.0147264		0.014288	0.0147264		0.014288	0.0154443		0.019965	0.005391	0.615666

	12			23			34			45			56			
%MO	0.26	0.52	0.7	0.65	0.35	0.65	0.65	0.35	0.65	0.65	0.35	0.65	0.7	0.52	0.26	
M DES	-41.648	83.29602	-112.129	-104.12	56.06463	-104.12	-104.12	56.06463	-104.12	-104.12	56.06463	-104.12	-112.129	83.29602	-41.648	
moments																
column	-41.648	45.81281	-78.4905	-72.884	30.83555	-72.884	-72.884	30.83555	-72.884	-72.884	30.83555	-72.884	-78.4905	45.81281	-41.648	
middle	0	37.48321	-33.6388	-31.236	25.22908	-31.236	-31.236	25.22908	-31.236	-31.236	25.22908	-31.236	-33.6388	37.48321	0	
bars																
column	5	6	9		4	9		4	9		4	9		6	5	
middle	4	5	4		4	4		4	4		4	4		5	4	
length																
column	1.8625	5.5625	3.3125		5.5125	3.3		5.5125	3.3		5.5125	3.3125		5.5625	1.8625	
middle	1.699	5.525	2.987		5.475	2.976		5.475	2.976		5.475	2.987		5.525	1.699	
volume	0.003222	0.0122	0.0083521		0.00879	0.0083208		0.00879	0.0083208		0.00879	0.0083521		0.0122	0.003222	0.181118
																Total X mat volume 0.796784

B.4 Shear Wall Sample Calculations

Sample Shear (seismic):

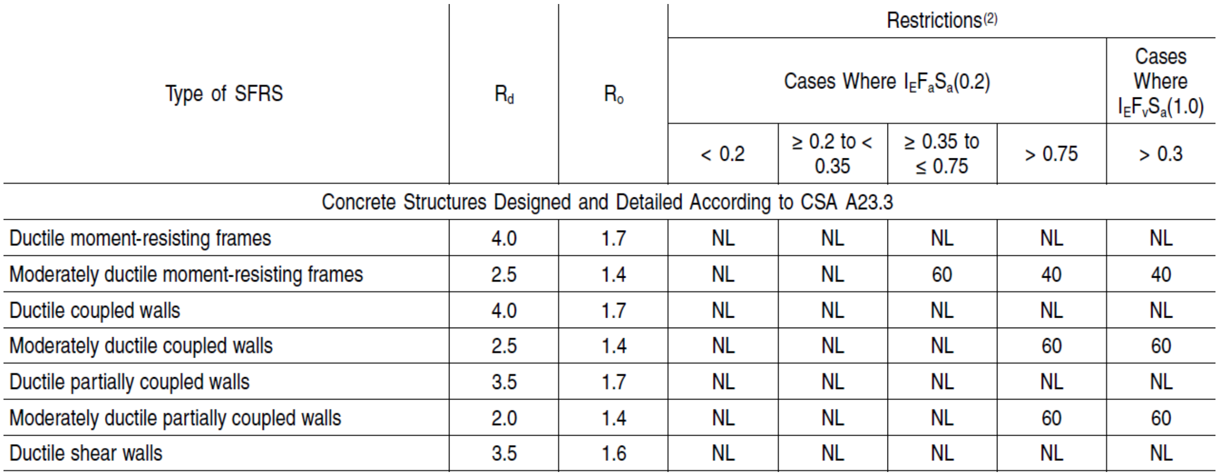
Sa (0.05)	Sa (0.1)	Sa (0.2)	Sa (0.3)	Sa (0.5)	Sa (1.0)	Sa (2.0)	Sa (5.0)	Sa (10.0)
0.216	0.262	0.219	0.165	0.116	0.059	0.029	0.007	0.003

$$T_a = 0.05(h_n)^{3/4}$$

$$T_a = 0.05(61)^{3/4} \qquad 4\text{-}8$$

$$T_a = 1.09$$

From NBCC 2015:



Type of SFRS	R_d	R_o	Restrictions[(2)]				
			Cases Where $I_EF_aS_a(0.2)$				Cases Where $I_EF_vS_a(1.0)$
			< 0.2	≥ 0.2 to < 0.35	≥ 0.35 to ≤ 0.75	> 0.75	> 0.3
Concrete Structures Designed and Detailed According to CSA A23.3							
Ductile moment-resisting frames	4.0	1.7	NL	NL	NL	NL	NL
Moderately ductile moment-resisting frames	2.5	1.4	NL	NL	60	40	40
Ductile coupled walls	4.0	1.7	NL	NL	NL	NL	NL
Moderately ductile coupled walls	2.5	1.4	NL	NL	NL	60	60
Ductile partially coupled walls	3.5	1.7	NL	NL	NL	NL	NL
Moderately ductile partially coupled walls	2.0	1.4	NL	NL	NL	60	60
Ductile shear walls	3.5	1.6	NL	NL	NL	NL	NL

Building weight was determined based on the material volume calculations from the spreadsheet.

Design considered maximum ground floor shear and moment at every floor.

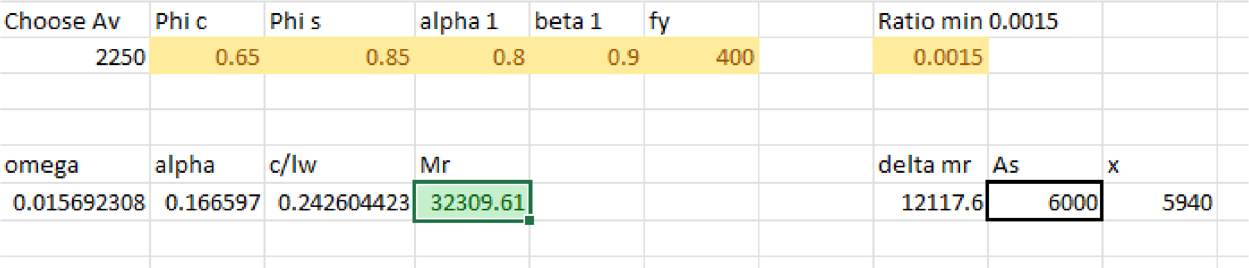
$$V = \frac{S(T_a)M_v I_E W}{R_D R_o}$$

$$V = \frac{(0.056)(1.1)(0.75)(100860)}{(3.5)(1.6)} \qquad 4\text{-}7$$

$$V = 837 \text{ kN}$$

Sample Moment:

$$M_r = 0.5\phi_s f_y A_{vt} l_w \left(1 + \frac{P_f}{\phi_s f_y A_{vt}}\right)\left(1 - \frac{c}{l_w}\right) \qquad 4\text{-}9$$



Choose Av	Phi c	Phi s	alpha 1	beta 1	fy		Ratio min 0.0015		
2250	0.65	0.85	0.8	0.9	400		0.0015		
omega	alpha	c/lw	Mr				delta mr	As	x
0.015692308	0.166597	0.242604423	32309.61				12117.6	6000	5940