

# **Influence of Sustainable Concrete Mix Designs on Costs and Global Warming Potential**

**By  
Sami Abu Shammeh**

**Under the supervision of:  
Dr. Leandro F.M. Sanchez**

**A thesis submitted to the Faculty of Engineering at the University of Ottawa in  
partial fulfilment of the requirements for the degree of**

**Master of Applied Science in Civil Engineering**



**uOttawa**

**Department of Civil Engineering  
Faculty of Engineering  
University of Ottawa  
Ottawa, Ontario, Canada**

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## ABSTRACT

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Pressure continues to increase globally within governments and various industries such as manufacturing and construction to embrace eco-friendly practices aiming to diminish CO<sub>2</sub> emissions; therefore, researchers worldwide started developing innovative eco-friendly materials such as concrete with supplementary cementitious materials (SCM); low cement concrete (LCC) using advanced mix design techniques such as PPM's and/or MP's; and recycled concrete aggregates (RCA), etc. These materials are at different stages of research for their use in structural application and have proven to have the same and/or superior performance to conventional concrete throughout the research completed in the past few years, but the concrete industry currently has a lack of knowledge on cost for the use of these materials which represents a current gap in the literature that needs further research. Since the construction industry's main constraint nowadays on all projects is the cost associated with the work, and since the use of innovative eco-friendly materials in infrastructure construction is becoming a requirement, the cost associated with these materials needs to be studied further. This study aims to evaluate the upfront cost impact and global warming potential of different sustainable concrete mixtures such as use of SCM's, PPM's, MP's, and RCA's in concrete mixtures. The direct cost of each of these concrete mixtures may vary due to a variety of factors such as market conditions, material availability, region, and supply/demand; therefore, the purpose of this study is to review the relative difference of these mixtures under same conditions. Trends in the construction industry show that due to resource constraints and new sustainability requirements, conventional concrete mixtures will become obsolete and will need to be replaced by innovative eco-friendly mixtures. Results of this study indicate that the use of PPM's, MP's and RCA's either individually or in combination are not just able to reduce the cost of concrete mixtures but also reduce the global warming potential (GWP). Two new parameters were established as part of this work, first was to simultaneously assess cost and eco-efficiency using a "carbon cost intensity" (CCI) factor; second was to simultaneously assess concrete's performance, economic impact, and environmental impact using a "Integrated Strength Cost Eco-Efficiency" (I-SCEE) coefficient.

**Keywords:** Low Cement Concrete; Recycled Concrete Aggregates; Cost; Global Warming Potential

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## LIST OF SYMBOLS / ACRONYMS / DEFINITIONS

ACRONYM / SYMBOL	MEANING	DEFINITION (IF REQUIRED)
RCA	Recycled Concrete Aggregate	Aggregates produced by crushing waste concrete.
LCC	Low Cement Concrete	Sustainable material made by reducing cement content
PPM	Particle Packing Model	Method for mix-design low-binder concrete with optimization of the particle size distribution and use of a q-factor.
MP	Mobility Parameter	Methodology for mix proportion using MPT & IPS
SCM	Supplementary Cementitious Materials	
CC	Conventional Concrete	Concrete made with natural aggregates (i.e. without any use of RCA). Control or companion mixes referred to in this project are conventional concretes.
GC	Green Concrete	Term referring to the sustainable concrete standard used within the industry
EMV	Equivalent Mortar Volume Method	The design procedure developed by Fathifazl et al. [1] for optimizing the hardened matrix of RCA Concrete
EV	Equivalent Volume Method	Mix-design method for concrete with RCA accounting for the difference in microstructure.
EMV-mod	Modified Equivalent Mortar Volume Method	Mix-design method for concrete with RCA accounting for the difference in microstructure modified to improve fresh state properties.
MPT	Maximum Paste Thickness	Maximum distance between coarser particles larger than 125 $\mu$ m
IPS	Interparticle Separation Distance	Average distance between two adjacent fine particles (smaller than 125 $\mu$ m)
NA	Natural Aggregates	Aggregates derived from traditional sources and that have not been used for any applications previously.
CA	Coarse Aggregates	Aggregates larger than 4.75mm
FA	Fine Aggregates	Aggregates smaller than 4.75mm
CRCA	Coarse Recycled Concrete Aggregates	Recycled Aggregates larger than 4.75mm
FRCA	Fine Recycled Concrete Aggregates	Recycled Aggregates smaller than 4.75mm
RM	Residual Mortar	The portion of the RCA comprised of hydrated cementitious materials and fine aggregates.

RCP	Residual Cement Paste	The portion of hydrated and unhydrated cement attached to residual fine material within FRCA material.
RMC	Residual Mortar Content	The percentage of RCA that is residual mortar. RMC is a physical property of RCA and unique to each aggregate sample
OVA	Original Virgin Aggregates	The natural coarse aggregate used to produce the source concrete for the RCA.
DRM	Direct Replacement Method	Design methods for RCA concrete that replace some portion of natural aggregates with RCA and do not account for the presence of residual mortar
DWR	Direct Weight Replacement	One of the approaches as part of the RCA DRM Method using weight of materials
DVR	Direct Volume Replacement	One of the approaches as part of the RCA DRM Method using volume of materials
WA	Water Absorption	ASTM C128 – 15 for Fine Aggregates ASTM C127 – 15 for Coarse Aggregates
SG	Specific Gravity	ASTM C128 – 15 for Fine Aggregates ASTM C127 – 15 for Coarse Aggregates
GWP	Global Warming Potential	Measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO <sub>2</sub> )
I-SEE	Integrated Strength Eco-Efficiency	
CCI	Carbon Cost Intensity	New term created as part of this work to combine cost and eco-efficiency
I-SCEE	Integrated Strength Cost Eco-Efficiency	New term created as part of this work to combine strength, cost, and eco-efficiency
PC	Portland Cement	
OPC	Ordinary Portland Cement	
FA	Fly Ash	
SF	Silica Fume	
BFS	Blast Furnace Slag	
PSD	Particle Size Distribution	
MS	Manufactured Sand	
NS	Natural Sand	
CF	Crushers fine	Two series of crushing and sieving
FG	Fully ground	Multiple series of crushing and sieving

LCA	Life Cycle Analysis	Systematic analysis of environmental impact over the course of the entire life cycle of a product, material, process, or other measurable activity
CSA	Canadian Standards Association	
ASTM	American Society for Testing & Materials	
CPFT	Cumulative Percentage Finer than d	
ACI	American Concrete Institute	
VSA	Volume Surface Area	
LF	Limestone Fillers	
f'c	Concrete Compressive strength	
RU	Re-used Concrete	Reused concrete material collected from demolition sites
RT	Returned Concrete	Returned concrete material to the concrete production facility and crushed on site.
Bi	Binder Intensity	Relationship between amount of binder required to obtain one unit of 28-day compressive strength in concrete.
Ci	Carbon Intensity	Relationship between amount of CO <sub>2</sub> emitted by the production of a material and one unit of 28-day compressive strength in concrete.

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## ACKNOWLEDGEMENTS

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First and foremost, I would like to acknowledge and express my sincerest gratitude to my supervisor Dr. Leandro Sanchez, who has been an instrumental contributor to not only my master's degree but also my career as a whole. I began working in Dr. Sanchez's research group in Fall of 2016 during my undergraduate studies and I cannot be more grateful for his continuous support, motivation, guidance, and mentorship throughout all these years. I will continue to regard Dr. Sanchez as my mentor for many years to come and will always consider him a close friend. Dr. Sanchez's passion and dedication to concrete technology is unmatched and is electrifying for everyone around him.

I dedicate this MASc program to my mother, father, wife, and my baby girl as this thesis would not have been possible without their love, support, and encouragement. Thank you to my Mother Ehsan Jarrar and Father Mahmoud Abu Shammeh for instilling a love for engineering in me, for encouraging me and supporting me throughout this journey. I owe sincere gratitude to them for moulding me into the man I am today. Thank you to my wife Zein Zaghloul and my daughter Jana Abu Shammeh for their unconditional love and support as they are the reason why I worked very hard to complete this degree.

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## FOREWORD

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This MASc thesis presents and analyzes the results of a comprehensive review on the role of sustainable concrete in the reduction of costs and CO<sub>2</sub> emissions (GWP). Sustainable concrete materials such as concrete with supplementary cementitious materials (SCM), low cement concrete (LCC) using advanced mix-design techniques, and recycled concrete aggregates (RCA) were reviewed and discussed with experts within the industry to gain valuable cost data to prepare a comparative analysis. The goal of this study is to form as the first part of a complete lifecycle cost analysis review which will evaluate the cost and GWP of the above materials. The expectation is that the use of these sustainable concrete mix designs is not just able to reduce the cost of concrete mixtures but also reduce CO<sub>2</sub> emissions by reducing the global warming potential compared to conventional concrete. Two new parameters were established as part of this work, first was to simultaneously assess cost and eco-efficiency using a “carbon cost intensity” (CCI) factor; second was to simultaneously assess concrete’s performance, economic impact, and environmental impact using a “Integrated Strength Cost Eco-Efficiency” (I-SCEE) coefficient.

The thesis is divided into six sections, with the core of the thesis corresponding to a scientific paper cover the specific objectives of the current research. To ensure that the content of this paper based MASc thesis is clear to readers, refer to the below summary of what’s included in each section:

- Chapter 1: Introduction to the work which includes brief overview of all the topics to be reviewed, Problem statement, and research program
- Chapter 2: Detailed literature review of the current state-of knowledge relevant to the concrete mix designs reviewed as part of this work.
- Chapter 3: Journal paper which evaluates the role of sustainable concrete mix designs in the reduction of concrete costs and mitigation of global warming.
- Chapter 4: Summary and conclusion of the project highlighting the main take-aways
- Chapter 5: Recommendations for future work
- Chapter 6: References

## CHAPTER 1: INTRODUCTION

### 1.1 BACKGROUND

Civil infrastructure is very critical for society, driving the economy and improving the quality of life for human beings. The increasing demand for infrastructure in the recent years has led to an increase in annual concrete production which therefore increases the demand for cement production since cement is one of the main components of concrete. The advantage that cement has over other binding materials is its superior hydraulicity property which helps in the preparation of good mortar. As shown in figure 1 graph (a), in year 2000 the annual world cement production was approximately 1500 million tons whereas in year 2014, the annual world cement production was approximately 4250 million tons which represents a 183% increase [2]. When looking at India's cement production specifically (figure 1 – graph b), it is estimated that from 2010 to 2050, it is projected to have an increase of 527% and this reinforces the concept that cement production is not slowing down and therefore it is essential to begin implementing sustainable production practices in order to mitigate or reduce climate change impacts [2]. Environmental sustainability is the top priority when looking at sustainability issues related to cement production since 7% of total anthropogenic carbon dioxide is generated from the cement industry. There are various possible options to improve sustainability which are by reducing the cement content required in concrete infrastructure or by modifying the cement production process by methods such as co-processing and blending [2]. Figure 2 illustrates the amount of global CO<sub>2</sub> emissions from cement production from 1928 to 2017, and this is a clear indication of a problem that needs to be mitigated to ensure a sustainable future for civil engineering infrastructure [3].

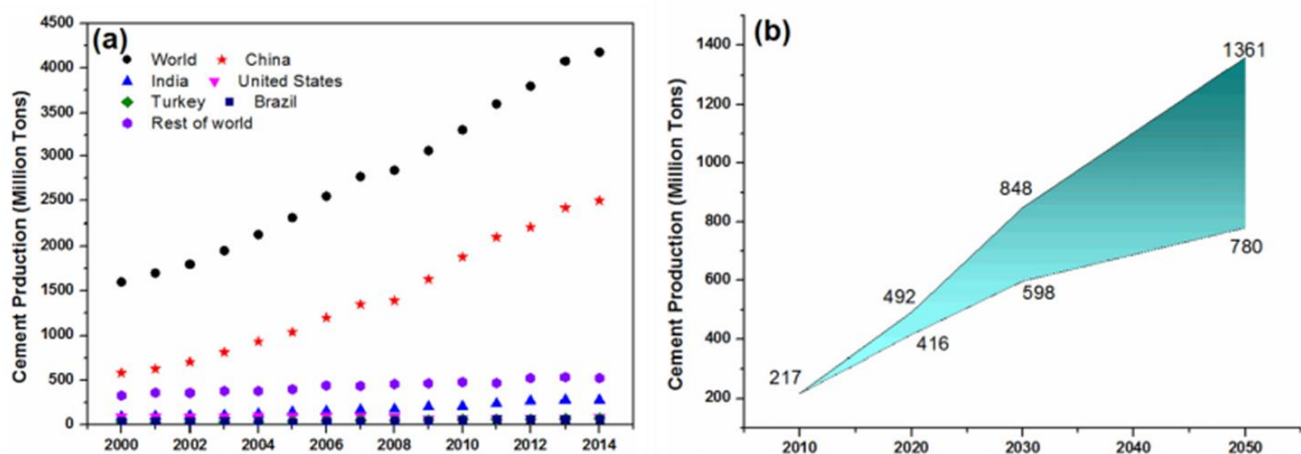
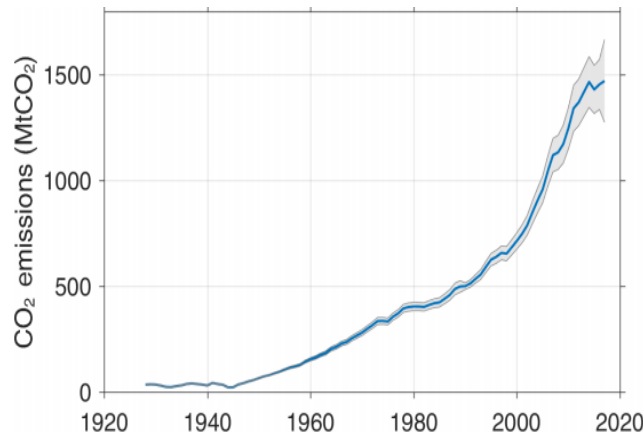


Figure 1 - Graph (a): Trends of Cement Production Per Year, Graph (b): Project Cement Demand in India [1]



*Figure 2 - Global process emissions from cement production from 1928 to 2017 [2]*

The focus of this study will be towards the economic impacts of the cement content within concrete as concrete is the most consumed construction material in the world after water and there is currently twice as much concrete used in construction as all other building materials combined [4]. The use of structural and non-structural concrete increased by 400% between 1990 and 2002, which has led to significant environmental impact worldwide [5] [6]. As Pressure is mounting in the construction industry to adopt more environmentally sustainable methods to reduce cement content and CO<sub>2</sub> emissions, there are several innovative eco-friendly materials that are currently being researched to mitigate this environmental impact and reduce cement content such as: Low Cement Concrete (LCC) using advanced mix design techniques and Recycled Concrete Aggregates (RCA)

## 1.2 ADVANCED MIX DESIGN TECHNIQUES

The concrete industry predominantly relies on a conventional method to mitigate its carbon footprint: replacing a portion of Portland cement (PC) with residues from other industries, known as supplementary cementing materials (SCMs). These SCMs, including fly ash (FA), silica fume (SF), and blast-furnace slag (BFS), are widely utilized in concrete technology. SCM's have been used historically as a partial replacement to cement by the concrete industry due it's lower cost, short & long-term performance benefits, and reduced carbon footprint. However, the global scarcity and depletion of these SCMs underscore the urgent need to explore alternative solutions for reducing the environmental impact of concrete. Diversifying approaches beyond SCMs is imperative to ensure sustainability in the construction sector and to address the challenges posed by diminishing SCM resources. The use of SCM's although effective is not considered a scientific approach to reduce carbon footprint and to reduce costs since the method is very standard and has limited development/improvement opportunities. The costs associated with the use of SCM's are also very common and well known within the concrete industry.

Recent efforts in concrete research have shown that there are novel methods that can effectively reduce carbon emissions while maintaining the structural integrity and functionality of concrete structures which ultimately could also reduce the cost of sustainable concrete mixtures. A few of the novel methods to be reviewed are: 1) Low Cement Concrete using advanced mix design techniques and 2) Recycled Concrete Aggregates (RCA). These methods are relatively new and the research on their performance and long-term behavior in structural applications is still ongoing. Several researchers around the world have studied the mix design, fresh/hardened state performance, and optimization of these concrete mixtures but there is still currently an apparent gap in the body of knowledge which is related to the economical aspect of these concrete mixtures. The majority of the concrete technology research worldwide focuses on the behavior and performance of these innovative materials and neglects the cost aspect of these materials. This is currently a gap in the literature that needs further research and improvement. The construction industry's main constraint nowadays on all projects is the cost associated with the work, and since the use of innovative eco-friendly materials in infrastructure construction is becoming a requirement on all projects, the cost of these materials needs to be studied further. Providing a cost analysis of these materials will provide owners and decision makers with the full circle of information they need to make the right decision in terms of which materials to use for different infrastructure projects. Since this is a relatively new topic in a very competitive concrete supply market, there is no defined methodology on how to compare the costs of the different concrete mixtures to understand the economical aspects. This study aims to begin the process of completing this comparison with more development to be completed in future studies.

The use of particle packing models to achieve low cement concrete has been studied by multiple researchers and it has been found that the use of particle packing models (PPMs) could lead to a significant reduction in the cement content of concrete by improving its aggregate's skeleton. With the reduction of cement content, the cost of the overall concrete mixture is expected to be reduced accordingly. PPM's approach is based on the idea of optimizing the particle size distribution (PSD) or grading of the aggregate's skeleton in concrete mixtures. Research by Yousef et. al [7] studied standard PPM employing the Alfred continuous PPM model which indicated that the use of packing models enables the development of LCC systems with superior performance in the hardened state while yielding approximately 25% reduction in cement content at the highest packing density. However, it's crucial to note that the fresh state properties of densely packed mixtures warrant special consideration. These properties could be enhanced by incorporating various additives such as plasticizers, fillers, or supplementary cementing materials (SCMs).

PPM mix designs were further developed by de Grazia [8] in two stages: 1) by introducing inert fillers in different quantities as a PC partial replacement by percentage since the PSD of the fillers and PC were quite similar; 2) by implementing a modified version of Alfred's PPM model which broke the PSD curve into two parts (i.e. the first from the smallest particle diameter to 100  $\mu\text{m}$  and the second from 100  $\mu\text{m}$  to largest particle diameter) using two distinct distribution factors with the addition of inert fillers to ensure more fines are brought into the mix. Results of this optimized PPM study show that it is possible to produce eco-efficient concrete without compromising the fresh and hardened properties of the material. This study showed improved fresh and hardened state properties while also further reducing the cement content which will likely further reduce the cost of the concrete mixtures.

While particle packing models (PPMs) are intended to enhance packing density and diminish porosity in concrete mixtures, densely packed and low-porosity systems may encounter challenges during the fresh state. Consequently, relying solely on PPMs is insufficient; instead, a comprehensive approach including mix proportioning for low-porosity systems and an examination of particle mobility is essential. This ensures that the concrete achieves desired fresh state properties while still benefiting from improved packing efficiency and reduced porosity facilitated by PPMs. A study using mobility parameters was completed by de Grazia [8] and the results showed that although the use of MP's can produce eco-efficient concrete without compromising the fresh and hardened states of the material and also further reducing the carbon footprint.

The use of recycled concrete aggregates is a sustainable alternative to traditional virgin aggregates, obtained by crushing and processing waste concrete. Utilizing RCA's in construction reduces the demand for natural resources and landfill space, while also reducing energy consumption and greenhouse gas emissions associated with concrete production. The use of RCA is not new in the field as it has been used for road underlay, backfill, and non-structural concrete applications for many decades. The lack of knowledge about the behavior of RCA in structural applications has led to misconceptions about the performance and durability of RCA concrete which has made codes and standards hesitant to incorporate RCA mix designs into their documents. In a recent study by Hayles [9], the application of the equivalent mortar volume method revealed a significant opportunity to decrease the cement and mortar content in concrete mixes. By factoring in the contribution of adhered mortar present on recycled concrete aggregates (RCAs), the total cement demand of the mix could be effectively reduced. This method enabled a notable reduction in cement content, lowering it from 314  $\text{kg}/\text{m}^3$  and 370  $\text{kg}/\text{m}^3$  for control mixes to as low as 162  $\text{kg}/\text{m}^3$  and 191  $\text{kg}/\text{m}^3$  for mixes containing RCAs, targeting strengths of 25MPa and 35MPa, respectively. A more optimized version of RCA mix designs was developed by

Ahimoghadam [10] which employed an equivalent volume method (EV) which was capable of efficiently improving the fresh state behaviour of RCA concrete without the need of chemical admixtures and therefore achieving a lower bi factor compared to the EMV method. The research completed by Hayles [9] and Ahimoghadam [10] was conducted with coarse RCA and therefore their studies were complimented by Macedo [11] which studied concrete made with fine recycled concrete aggregates with different mix design methods. The conclusion from the study by Macedo [11] provided more insight on the overall behaviour of FRCA concrete presenting different ingredients (i.e. MS vs NS), manufacturing processes (i.e. CF vs FG) and mix-design techniques (DRM, EV and PPMs).

All of the previously cited research studies have proven that these materials have the same performance or even superior performance to conventional concrete mixtures; yet the concrete industry currently has a lack of knowledge on the life cycle cost and global warming potential of these materials. Trends in the construction industry show that due to resource constraints and new sustainability requirements, conventional concrete mixtures will become obsolete and will need to be replaced by innovative eco-friendly mixtures. This research program was developed to address the first step in the lifecycle analysis which is to compute the material cost and global warming potential of these sustainable mix designs as well as develop parameters to co-relate the cost of these materials to performance and environmental impact.

### 1.3 PROBLEM STATEMENT & OBJECTIVES

The research program was developed to address and fill a gap within the industry body of knowledge on the influence of sustainable concrete mix designs on overall cost and global warming potential. The three pillars of sustainability are Environmental, Social, and Economical. Researchers around the world have focused on the environmental and social implications of these mix designs by evaluating their fresh and hardened state properties but little research is present on their economical impact and therefore the aim of this study is to provide cost & GWP evaluation as a first step to a complete life cycle cost analysis. This study aims to analyze and quantify the cost and global warming potential of sustainable concrete mix designs through the use of low cement concrete and recycled concrete aggregates technologies and compare them to standard industry used mix designs (conventional CSA/ACI Mixes and SCM Mix designs). The current industry standard for sustainable concrete mix designs is the use of SCM's which is branded as "green concrete" and typically has a higher price in the market than conventional mixes. The reason for the higher price is primarily related to marketing of a more sustainable product when compared to conventional concrete but in fact, the cost of it is slightly lower to concrete suppliers. All of the previously noted mix designs have proven that these materials have the same

performance or even superior performance to conventional concrete mixtures, but the concrete industry currently has a lack of knowledge on the life cycle cost of these materials and therefore full attention is required to the material cost to ensure that decision makers have this valuable information so they can enable change in the concrete industry. The goal of this study is to showcase that the use the previously mentioned technologies are not just able to reduce the cost of concrete mixtures but also reduce the CO<sub>2</sub> emissions. The direct cost of each of these concrete mixtures may vary due to a variety of factors such as market conditions, material availability, region, and supply/demand; therefore, the purpose of this study is to review the relative difference of these mixtures under same conditions and not to specifically focus on the exact cost of each mixture. Once the cost and GWP of the concrete mixtures is established, the objective of this study is to develop a relationship between the cost of the material, GWP and performance.

## 1.4 RESEARCH PROGRAM

The research program began by researching different mix design technologies which ultimately resulted in the selection of low cement concrete using advanced mix proportion techniques and recycled concrete aggregates using different mix proportion methods. Detailed review was completed for each mix design method and all the data was summarized in the materials and methods section. Market research through collaboration with multiple concrete suppliers was completed to establish baseline pricing for conventional concrete and industry standard for green concrete (SCM mixes) and all the data was broken down by component to provide the ability to evaluate the pricing of alternate sustainable concrete mix designs. A total of 74 mixes were selected and evaluated for cost, GWP, and binder/carbon/I-SEE intensities. Costing data was developed in collaboration with industry partners and was then used to compare to conventional concrete and industry “green concrete” mix designs. The results showcase the role of sustainable concrete in the reduction of concrete costs and global warming potential. Based on the results of cost and GWP, two new relationships were required to be added to the body of knowledge: first was to simultaneously assess cost and eco-efficiency using a “carbon cost intensity” (CCI) factor; second was to simultaneously assess concrete’s performance, economic impact, and environmental impact using a “Integrated Strength Cost Eco-Efficiency” (I-SCEE) coefficient. The remaining stages for a complete life cycle cost analysis have been identified and summarized for further review and research.

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## CHAPTER 2: LITERATURE REVIEW

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A review of the relevant literature for the major constituents of the concrete mix designs as part of this study is prepared and presented below. The literature review has been split into 5 main sections: 1) Use of Supplementary Cementitious Materials; 2) Particle Packing Models; 3) Mobility Parameters; 4) Recycled Concrete Aggregates; and 5) Sustainability/Eco-Efficiency in Concrete Industry.

### 2.1 SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCM'S)

In recent years, the incorporation of supplementary cementitious materials (SCMs) has gained significant attention due to their potential to enhance various properties of concrete while reducing its environmental footprint. This literature review explores the types of SCM's, extraction processes, utilization, advantages, and disadvantages of SCMs in concrete. The incorporation of SCM's in concrete has set the current standard for green concrete within the concrete supply industry and the overall construction industry. SCM's encompass a diverse range of materials, including fly ash, slag cement, silica fume, and natural pozzolans such as calcined clay, rice husk ash, and volcanic ash. These materials are typically industrial by-products or natural substances with pozzolanic or hydraulic properties, which react with calcium hydroxide in the presence of moisture to form cementitious compounds.

#### 2.1.1 TYPES OF SCM'S

1. **Fly Ash:** derived from the combustion of pulverized coal in power plants, stands as one of the most prevalent supplementary cementitious materials (SCMs) utilized in concrete production. Characterized by its spherical particles, fly ash significantly enhances the workability, durability, and chemical resistance of concrete [11]. Fly ash serves to compensate for any deficiency in fine materials, potentially augmenting the flowability and finishing ability of concrete mixtures. Fly ash is classified into Class C and Class F, as per ASTM C618, these designations delineate distinct properties. Class C fly ash contains high calcium content alongside low carbon levels, and offers robust pozzolanic and cementitious attributes, rendering it suitable for high-performance mixtures where early-age strength is paramount. Conversely, Class F fly ash, with its low calcium composition, effectively moderates heat generation during concrete curing, making it an ideal candidate for mass placements and high-strength applications, particularly in hot weather climates. Furthermore, its capacity to provide commendable sulfide and sulfate resistance to concrete mirrors that of Type V (CSA Type 50) cement [12].

2. **Slag Cement:** Slag cement is also referred to Ground granulated blast furnace slag (GGBFS) and is produced by the rapid cooling of molten blast furnace slag. Slag cement is rich in calcium silicate and aluminate compounds and is ground down to powder form and acts with hydraulic properties when combined with water. Its incorporation in concrete enhances long-term strength development, reduces heat of hydration, reduces permeability, and mitigates alkali-silica reaction [13]. GGBFS for concrete must meet the specifications of ASTM C989 and CSA A23.5.
3. **Silica Fume:** Silica fume is a by-product of silicon metal and ferrosilicon alloy production and is characterized by its exceptionally fine particles and high silica content. Incorporating silica fume into concrete mixtures entails filling the voids between cement particles, thereby augmenting the matrix's density and conferring enhanced strength, durability, and resistance to chemical attack. Its remarkable pozzolanic activity catalyzes the formation of additional calcium silicate hydrate (C-S-H) gel, fostering densification of the cementitious matrix and reducing permeability. Silica fume's ultrafine particle size and expansive surface area shows improved bonding between cement paste and aggregates, thereby enhancing mechanical properties and minimizing susceptibility to cracking and deformation. Silica fume is defined within ASTM C1240 and CSA A23.5, it is particularly advantageous for applications in aggressive environments such as marine structures, bridges, and industrial facilities and has capacity to mitigate alkali-silica reaction (ASR) and curtail chloride ion penetration [13] [14].
4. **Natural Pozzolans:** These materials, sourced from naturally occurring volcanic or sedimentary deposits, exhibit pozzolanic properties when finely ground and activated with lime. Examples of these materials are: calcined clays, shale, and metakaolin. They offer similar benefits to industrial SCMs and are often used in regions where industrial by-products are scarce [14]. Natural pozzolans are classified by ASTM C618 with their use in concrete referenced in ACI 232.1. In general, these processed clay and shale materials are heat treated and ground to powder form to help control temperature effects in mass concrete, improve resistance to sulfate attack and mitigate alkali silica reaction. Natural pozzolans are utilized as a cement replacement material in the range of 15% to 35%, contingent upon project requirements, natural pozzolans offer a sustainable alternative for enhancing concrete performance.

The extraction and processing of SCMs vary depending on their nature and the region. Fly ash and slag are obtained as by-products from industrial processes, requiring minimal processing before incorporation into concrete. Silica fume is collected from the exhaust gases of silicon and ferrosilicon production furnaces and processed to remove impurities. Natural pozzolans are mined, ground, and activated to enhance their reactivity

with lime. SCMs are typically used as partial replacements for Portland cement in concrete mixtures. The replacement level varies depending on the specific material and desired performance characteristics of the concrete. Incorporating SCMs reduces the clinker content in cement, thereby decreasing the carbon footprint associated with concrete production. Moreover, SCMs improve the workability, durability, and long-term performance of concrete structures. There is very limited room for improvement in concrete mix designs with the use of SCM's as their use is regulated by standards and is a function of replacement of cement by mass.

### 2.1.2 CODES & STANDARDS FOR USE OF SCM'S

The maximum allowance for supplementary cementitious material (SCM) replacement in concrete is typically governed by standards such as those provided by the Canadian Standards Association (CSA) and the American Concrete Institute (ACI). These standards outline guidelines and specifications for the use of SCMs in concrete mixtures to ensure adequate performance and durability. However, it's important to note that the maximum allowable replacement percentage can vary depending on factors such as the type of SCM, specific project requirements, and regional regulations. According to the CSA A23.1 standard, the maximum allowable replacement of cement with SCMs typically ranges from 15% to 70% by mass of the total cementitious material content. This percentage may vary based on the type of SCM used and its specific characteristics. Refer to table 1 below extracted from CSA 3000-08 which shows the maximum allowable limits for the use of SCM's [15]:

Table 1 - CSA3000 Maximum Allowable SCM Proportions

Type	Name
N Type	Name
F N	Natural pozzolans
Cl F	Fly ash with low calcium oxide (CaO) content
Cl CI	Fly ash with intermediate calcium oxide content
Sf CH	Fly ash with high calcium oxide content
Sf SF	Silica fume with high silicon dioxide (SiO <sub>2</sub> ) content
S SFI	Silica with intermediate SiO <sub>2</sub> content
Bl S	Ground granulated blast-furnace slag
— BMb	Blended supplementary cementing materials (see Clause 5.2)

**Note:** For materials other than those listed above that fall outside the scope of this Standard (e.g., quenched ground bottom ash, manufactured and other metallurgical slags, and silica fume with less than 75% SiO<sub>2</sub>), see CSA A3004-E1.

**Table 9**  
**Table 9**  
**Blended hydraulic cement and blended supplementary cementing materials proportions**  
(See Clauses 3 and 4.2.2.)

Component percent limits	Binary blended hydraulic cements produced with				Ternary* and quaternary blended hydraulic cement
	N	FA (F, CI, CH)	S	SF (SE, SFI)	
Supplementary cementing materials, maximum %	40	50	70	15	60
Portland cement, minimum %	60	50	30	85	40

\*In a ternary blend containing silica fume and slag, the maximum supplementary cementing materials content shall be increased to 70% and the minimum cement content shall be decreased to 30%.

**Notes:**

- (1) The proportions of each type of supplementary cementing material in any blended hydraulic cement shall not exceed the individual maxima specified in this table for binary cements. In the case where more than one fly ash is utilized in a blended hydraulic cement, the sum of proportions of the ashes shall not exceed 50%.
- (2) Blended cements containing natural pozzolans shall have a minimum portland cement content of 60%.

Similarly, the ACI 318 Building Code Requirements for Structural Concrete, provides the maximum allowable replacement of cement with SCMs in the US and it is in the range of 10% to 50%, depending on factors such as the type of SCM, project specifications, and performance requirements. Refer to table 2 below extracted from ACI-318-14 which shows the maximum allowance for limits for the use of SCM's:

*Table 2 - ACI-318-14 Maximum Allowable SCM Proportions*

<b>Cementitious materials</b>	<b>Maximum percent of total cementitious materials by mass</b>
Fly ash or other pozzolans conforming to ASTM C618	25
Slag cement conforming to ASTM C989	50
Silica fume conforming to ASTM C1240	10
Total of fly ash or other pozzolans and silica fume	35
Total of fly ash or other pozzolans, slag cement, and silica fume	50

## 2.2 LOW CEMENT CONCRETE (LCC)

### 2.2.1 PARTICLE PACKING MODELS (PPMS)

In standard concrete mix designs, the cement content used is typically high and is empirically selected as a function of the targeted consistency and water-to-cement (w/c) ratio needed to build a required strength along with the maximum size and volumetric amount of the coarse aggregate [16] [17]. In such methods, there is no thorough evaluation and selection of the materials gradation (i.e. particle size distribution - PSD). It has been found that if the aggregate skeleton is improved through the use of particle packing models (PPMs), then this could lead to significant reduction in the binder(cement) content required and therefore improving the eco-efficiency [18]. PPMs approach is based on the idea of optimizing the particle size distribution and the overall grading of the aggregates mix in order to achieve a tightly packed mix and therefore reducing the binder required. [19] [20] There are two different types of PPMs which are: discrete models and continuous models. In concrete technology applications, discrete models, as defined by Brouwers [21], are procedures tailored to handling narrowly defined size classes of particles, such as monodisperse, bimodal, or even narrow size cuts of multimodal particles. These models are particularly relevant for packing multimodal distributions comprising "n" discrete size classes of particles, known as gap-graded systems [21]. Discrete models can be split into two grading categories, either uniform grading or discontinuous grading which are shown in figures 3 and 4. Conversely, continuous particle packing models focus on particles with continuous sizes present in the mixture, ensuring no gaps throughout the entire particle size distribution (PSD). Additionally, these models assume a similarity condition for particle packing, where the arrangement of particles surrounding each particle in the distribution remains consistent, irrespective of the particle size [22] as shown in figures 3 and 4. Conventional concrete and discrete PPMs do not make the best use of binder as they do not consider the sizes of all aggregates at the right proportions to reduce the quantity required to bind all the aggregates together. The most efficient use of PPMs is continuous PPMs as they enhance the aggregate skeleton and achieve a more efficient use of the binder by sizing the particles with no gaps throughout the particle size distribution. Although the discrete approach is theoretically true, it is not practical to be achieved in actual applications of concrete designs; continuous distributions are normally found in nature which is why it is preferred to be used when developing mix designs for structural applications. As shown in figure 1, continuous well graded PSD, requires the least amount of binder to agglomerate all the aggregates together whereas the single uniform sized and poorly discontinuous graded cylinders require substantially more binder to fill all the pores. This is why the main focus of this work is continuous well graded PSD's which matches reality.

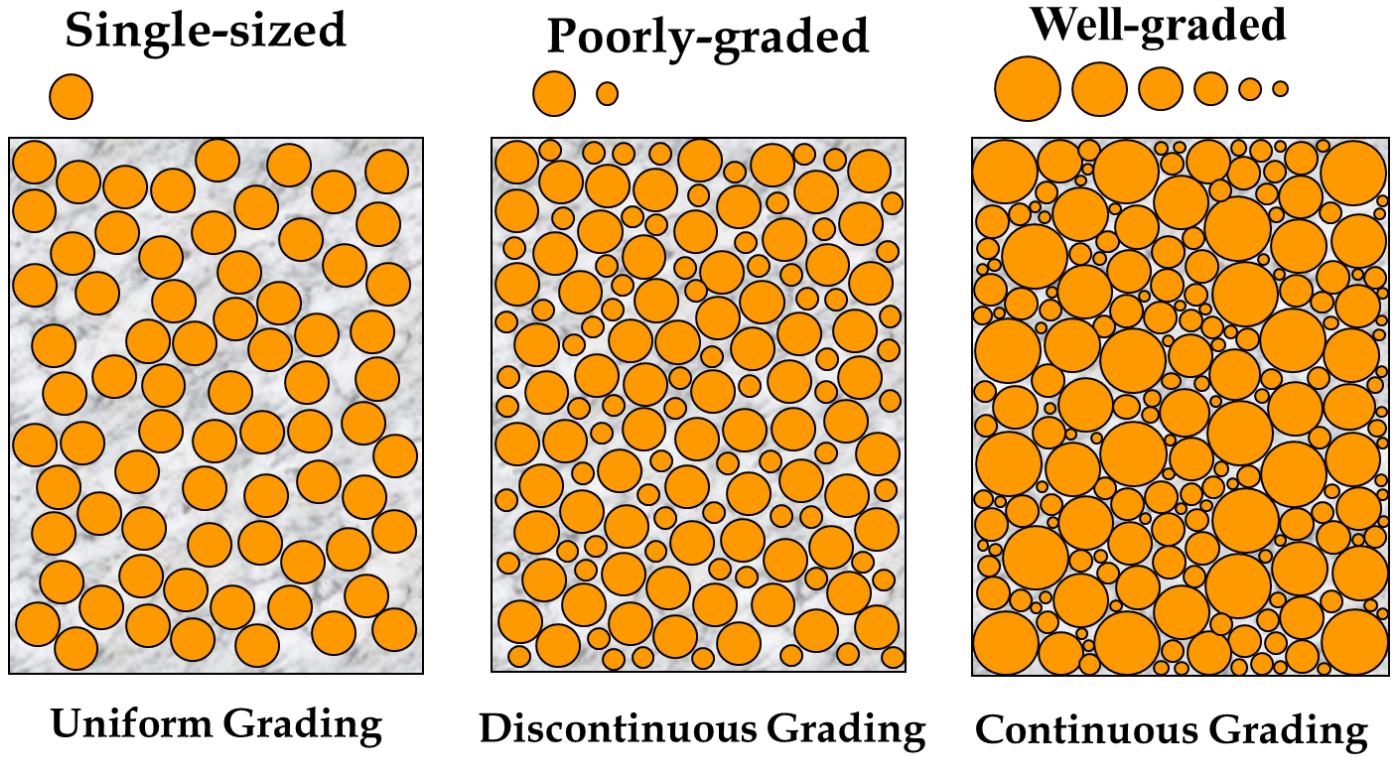


Figure 3 - Concrete cylinders showing single sized, poorly graded, and well-graded aggregate distributions [16]

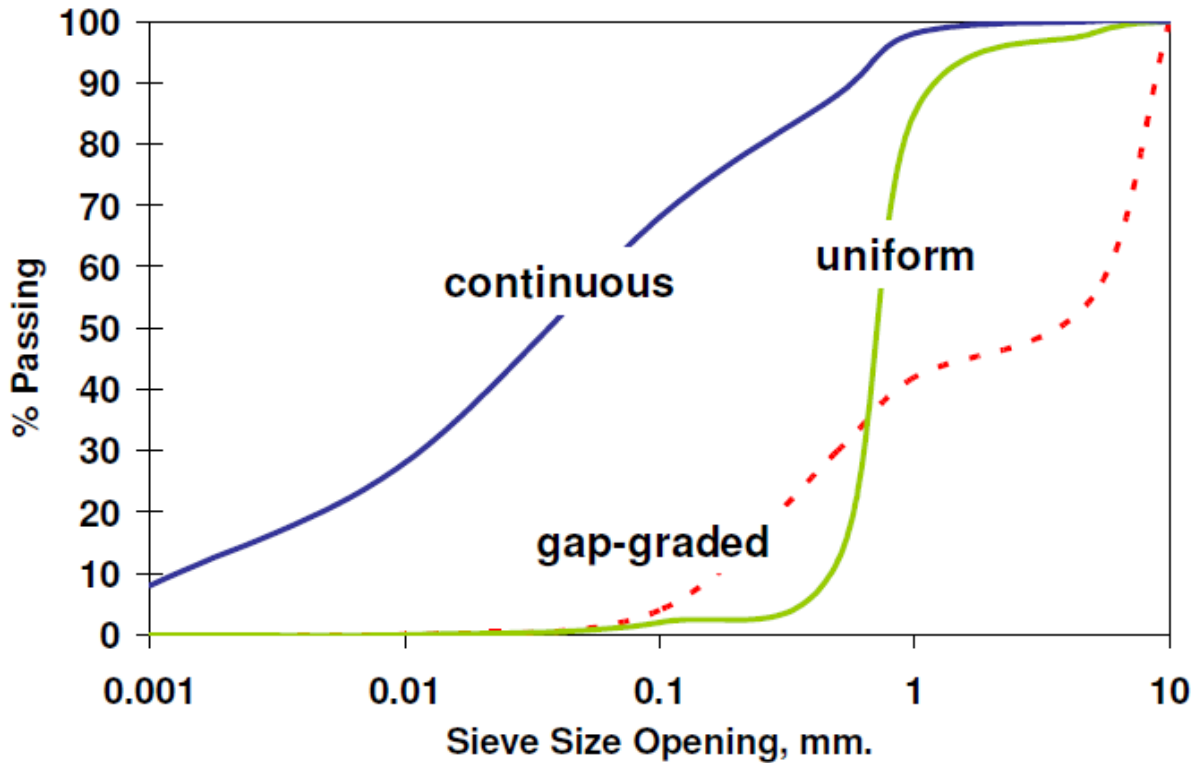


Figure 4 - Particle size distribution graph showing % passing vs sieve size [26]

### 2.2.1.1 CONTINUOUS PARTICLE PACKING MODELS

Continuous PPMs have been in development since the 1900's and they continue to be optimized. The first continuous PPM was brought by Fuller and Thompson in 1907 and continued to be optimized for applications not just limited to concrete mix designs. The principle of optimizing particle packing models is to improve the aggregate skeleton of the concrete mixture to ensure maximum density without impacting other fresh and hardened state properties. Although the fuller continuous PPM model ensures continuous grading, it did not provide the highest packing density and it only investigated aggregates in concrete mixes and not the whole mix. Despite the age of the fuller model, it remains as the base for proportioning the aggregate for concrete mixes in many national standards [18]. In the "Fuller Thomson model", the "ideal" grading curve is the one that maximizes packing density.

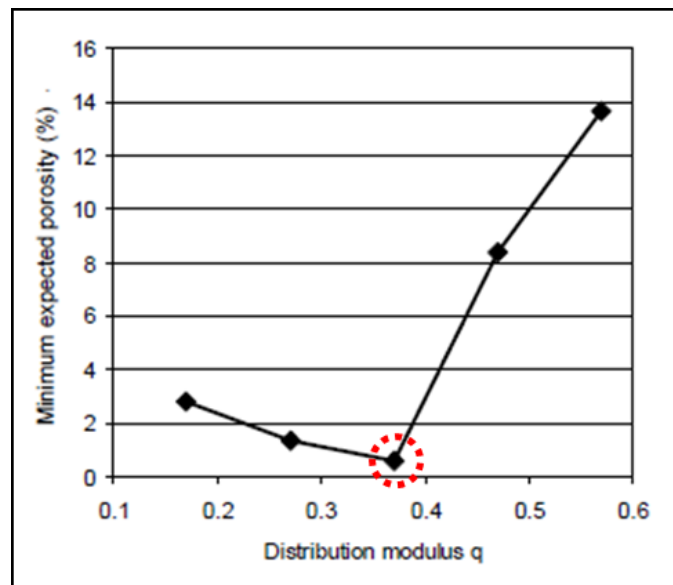
$$CPFT = \left(\frac{d}{D}\right)^n \times 100$$

Where CPFT is the cumulative percentage finer than d, D is the maximum particle size, d the given particle size, and n was found to be optimal at 0.5. However, n was recently changed to 0.45 [23]. Andreasen followed the work completed by the "Fuller Thomson model" and recognized that in real life the finest particles of a given material are not infinitesimally small but are finite in size. The particle packing model used for this research program is the latest approach which recognizes the need to have a finite size for the smallest aggregate as this was not considered before. The latest approach is the modified Andreasen model also called the Alfred model which is represented by the following equation where the q factor represents the distribution coefficient for defined minimum and maximum particle sizes, CPFT is the cumulative volume percent finer than, d is the particle size, d<sub>0</sub> is the minimum particle size, and D is the maximum particle size [22].

$$CPFT = \left(\frac{d - d_0}{D - d_0}\right)^q \times 100$$

The above power function is what's used to describe a continuous particle size distribution with a distribution factor to adjust the shape of the distribution curve. Andreasen suggested that the optimal q factor should range between 0.33 and 0.50, with a minimal particle size, d<sub>0</sub>, and equal to zero [20]. These values were obtained through mathematical and theoretical models. According to Fruhstofer and Aneziris [24], experimental work showed that the tightest packing model can be achieved when the q factor is equal to 0.37, and if distribution factor increases beyond 0.37, then the porosity of the system rises instantly. They also claimed that a q of 0.37 would bring the best possible benefits to the hardened state of concrete along with a decrease in the binder content of the mixture.

This was further validated by Vogt through the numerical approach proposed by Funk and Dinger using the Westman and Huggill porosity equations which was presented in his relation between the intergranular porosity and q-factor as shown in Figure 5 [25]. The literature validated that the highest theoretical packing density (lowest porosity) is achieved with a distribution factor of 0.37, however there was no qualitative data for the different properties in the fresh and hardened state using distinct q values.



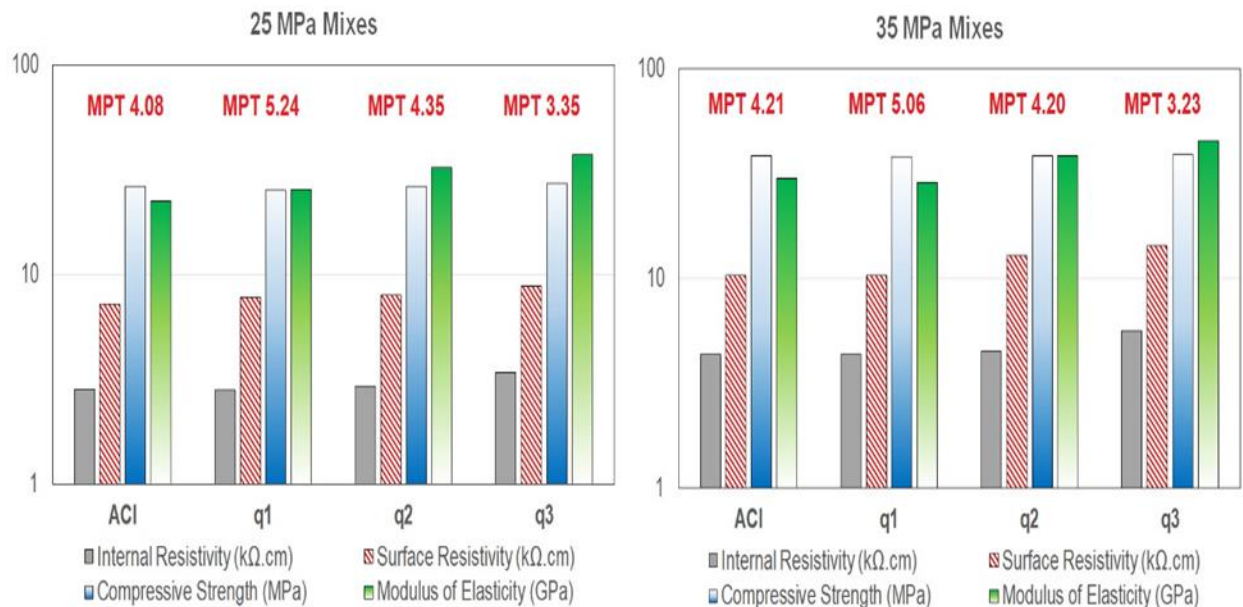
*Figure 5 - Graphical relation between porosity and the distribution factor (q) [18]*

It is worth noting that although the Alfred model is the latest continuous PPM approach, it still does not address some of the parameters that are not practical within a continuous PPM such as: assumptions of perfect spheres, smooth particle surfaces and no attracting or repelling forces between particles which do not necessarily happen in reality. Figure 3 (right most grading) illustrates a continuous PPM with the presence of various particle sizes but does not take into account the reality of morphology (i.e. shape and texture), porosity (i.e. within the aggregate particles and cement paste), interaction effects (i.e. loosening, wall and wedging effects) and different compacting techniques. The parameters stated above are considered opportunities for further improving PPM's and require further advancement to ensure ongoing development of PPM's. Recent research has focused on the porosity parameter by studying the topic of mobility parameters (MP) and then combined PPM's & MP's to show the impacts of this improvement. Refer to section 1.3 for the background regarding mobility parameters and how they can further improve the fresh state behavior of sustainable concrete mix designs.

### 2.2.1.2 FRESH AND HARDENED STATE OF STANDARD PPM MIX DESIGNS

Yousef et al. [7] used the Alfred particle packing model to develop the low cement concrete mix designs and three distributions factors were selected:  $q_1=0.26$ ,  $q_2 = 0.31$ , and  $q_3=0.37$  which represent low, moderate, and high particle packing distributions respectively. The results confirmed that the use of the Alfred PPM model was capable of improving the hardened state (i.e. compressive strength, modulus of elasticity, bending flexure) and durability related (resistivity) properties of conventional concrete mixtures. The mix developed with the highest  $q$  factor ( $q_3 = 0.37$ ) showed superior performance compared to all other mixes but represented challenges in the fresh state properties that required further review and attention. The mixes developed by Yousef et al. were used as the standard PPM mix design as part of this review. While the use of chemical admixtures was able to improve the fresh state behavior and consistency of the mix developed with the highest  $q$  factor ( $q_3 = 0.37$ ), that approach did not improve the eco-efficiency of the concrete which is why the optimized PPM mix design discussed in section 1.2.3 has further contributed to the body of knowledge to resolve this issue.

Taking a closer look at the hardened state results of the standard PPM mix designs, refer to figure 6 below showing the comparison between the different  $q$  factors as well as to a standard ACI conventional mix.



*Figure 6 - Comparison between hardened state properties and MPT for standard PPM mixes [6]*

Analyzing the results shown above one notices that as soon as the distribution factor increases ( $q$ -value), the system becomes denser, which lessens the overall number of voids and thus improving durability and decreasing the binder amount required which did not impact the overall performance of the material.

### 2.2.1.3 FRESH AND HARDENED STATE OF OPTIMIZED PPM MIX DESIGNS

De Grazia [8] further developed the work completed by Yousef et al. [7] by introducing fillers as a partial PC replacement by percentage and also by developing a modified version of Alfred’s model which splits the PSD into two parts: first from DS to 100  $\mu\text{m}$  and the second from 100  $\mu\text{m}$  to DL. Two distinct distribution factors were selected:  $q=0.37$  for the coarser particles (greater than 100  $\mu\text{m}$ ) and  $q=0.21$  for the finer particles (smaller than 100  $\mu\text{m}$ ). The lower coefficient factor (0.21) selected for the first part of the PSD (fine particles) aimed to improve the fresh state properties of the mixture which was a challenge in the previous work (Yousef et al.). The mixes developed by De Grazia were used as the optimized PPM mix designs as part of this review and they targeted 3 cement content boundaries: 1) 261-282  $\text{Kg/m}^3$ ; 2) 197-214  $\text{Kg/m}^3$ ; 3) 149-161  $\text{Kg/m}^3$ . The fresh state behavior was assessed through a rheometer presenting a shear thinning behaviour and thus might be used in applications under high torque regimes such as pumped and/or vibrated concrete [8]. Hardened state results for these optimized mixes are illustrated in the figure 7 which show that all mixes performed well and also confirmed that the densely packed systems using PPMs and distribution factor of 0.37 seem to present the best durability-related properties which is attributed to overall lower porosity, permeability along with lower coarse maximum paste thickness.

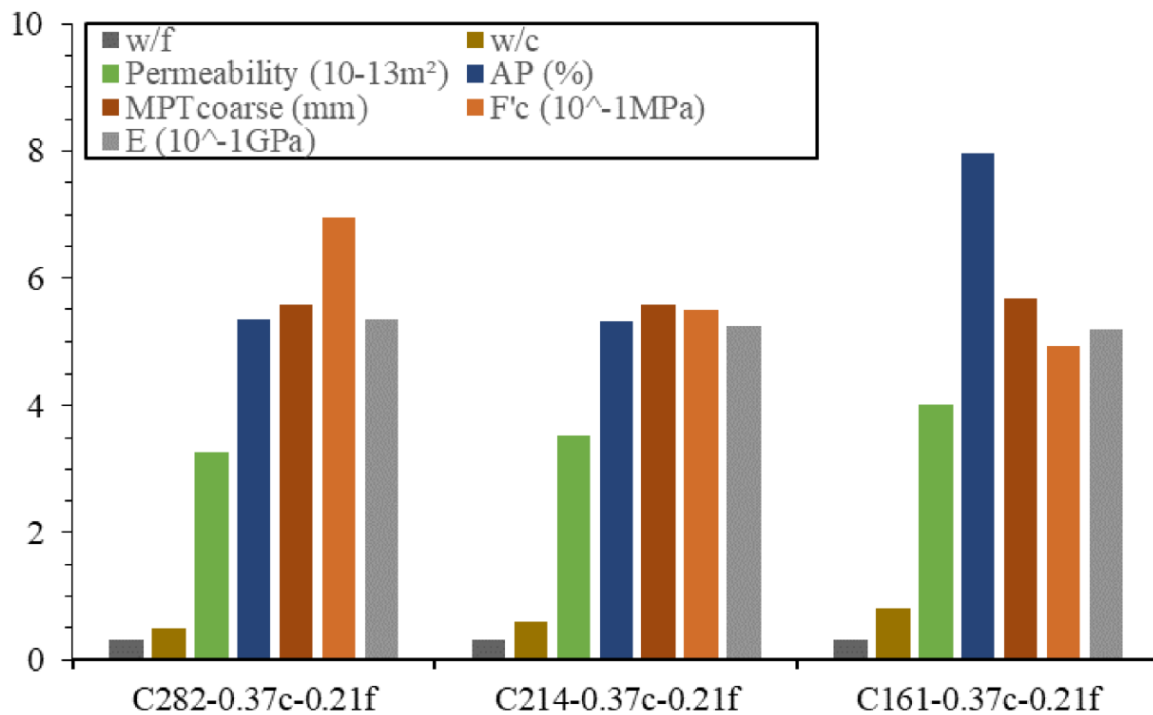


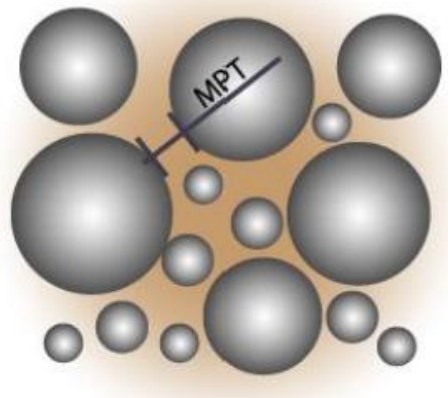
Figure 7 - Comparison between hardened state properties for optimized PPM mixes [7]

## 2.2.2 MOBILITY PARAMETERS

Mobility parameters (MP) are concepts used to understand the behavior of concrete mixtures in the fresh state and the use of MP's is useful to help further evaluate and improve fresh properties in high packing density systems. In concrete technology, there are two main mobility parameters studied which are: Interparticle Separation Distance (IPS) and Maximum Paste Thickness (MPT). Both parameters are critical for understanding and optimizing the microstructure and mechanical properties of concrete mixes and play a significant role in the overall performance of concrete, influencing its workability, durability, and strength. The literature highlights the interaction between IPS and MPT and their combined effect on concrete properties. By optimizing these parameters, concrete mixes can achieve a balance between workability, strength, and durability. Techniques such as particle packing optimization, the use of SCMs and nano-materials, and chemical admixtures have been studied extensively for this purpose. Research also points towards the development of models and tools to predict the optimal IPS and MPT for specific mix designs, taking into account the characteristics of the materials used and the performance requirements of the concrete.

### 2.2.2.1 MAXIMUM PASTE THICKNESS (MPT)

MPT represents the average maximum distance between the coarser particles larger than  $125\mu\text{m}$  which is the cement paste coating the coarse aggregates in a concrete mix. A visual representation of MPT is shown in figure 8 below. It is an essential factor in determining the mix's workability and the concrete's final density and strength. The MPT is influenced by the aggregate grading, shape, surface texture, and the volume of paste in the mix. Optimizing the MPT can lead to significant improvements in concrete properties. For instance, a thinner maximum paste thickness can enhance strength by reducing the volume of potentially weaker cement paste in the mix. However, it must be balanced to ensure adequate workability and to avoid harsh mixes that are difficult to place and compact [26].



*Figure 8 - Maximum Paste Thickness of Coarse Aggregates*

Since the space between coarse particles relies on the cement paste volume and, consequently, the amount of fine particles, concrete flow will be greatly influenced by the PPM selected on the mix- design. There are multiple ways to quantify MPT in literature, the one used in this work was defined by De Larrard which is represented in the following equation:

$$MPT = D_{\max} \left( \sqrt[3]{\frac{g^*}{g}} - 1 \right)$$

Where  $D_{\max}$  is the maximum aggregate size;  $g$  is the aggregate volume in a unit volume of concrete, which can be easily derived from the mixture proportioning; and  $g^*$  can calculate by using the following equation:

$$g^* = 1 - 0.47 \sqrt[5]{\frac{D_{\min}}{D_{\max}}}$$

Where  $D_{\min}$  is the minimum sized aggregate corresponded to 10% passing, and  $D_{\max}$  is the maximum sized aggregate corresponded to 90% passing.

### 2.2.2.2 INTERPARTICLE SEPERATION DISTANCE (IPS)

IPS refers to the average distance between the two adjacent fine particles (smaller than  $125\mu\text{m}$ ) which includes distances between cement grains as well as between cement grains and supplementary cementitious materials (SCMs) if they are present. This parameter is crucial because it directly affects the rheology of the cement paste and, consequently, the concrete. IPS can be considered equal to the total amount of fluid (water) that separates fine particles, as illustrated in figure 9 below. Research has shown that a lower IPS can result in a denser microstructure, leading to improved strength and durability. However, if the IPS is too low, it can adversely affect the workability of the concrete mix resulting in poor hydration since water can become trapped among fine particles and thus not be able to percolate and hydrate all binder particles as show in part a of figure 9 below. Studies have also explored how the manipulation of IPS through particle packing models and the use of ultrafine particles can enhance the performance of concrete [26]. Dinger and Funk have established an analytical equation to calculate IPS which is:

$$IPS = \frac{2}{VSA} \left[ \frac{1}{V_s} - \frac{1}{(1 - P_{of})} \right]$$

Where IPS is the Interparticle Spacing in a slip, VSA is the calculated volume surface area per cubic centimetre of powder,  $V_s$  is the volume fraction solids,  $P_{of}$  is the pore fraction assuming the densest packing.

Since PPM's consider all particles as spherical which is one of the reasons for incorporating IPS, IPS is calculated based on the VSA to account for the different particle shapes. VSA can be calculated from the SSA as follows

$$VSA = SSA * \rho_{part}$$

Where VSA is the volume surface area (m<sup>2</sup>/g), SSA is the specific surface area (m<sup>2</sup>/g), and  $\rho_{part}$  is the particle density (g/cm<sup>3</sup>).

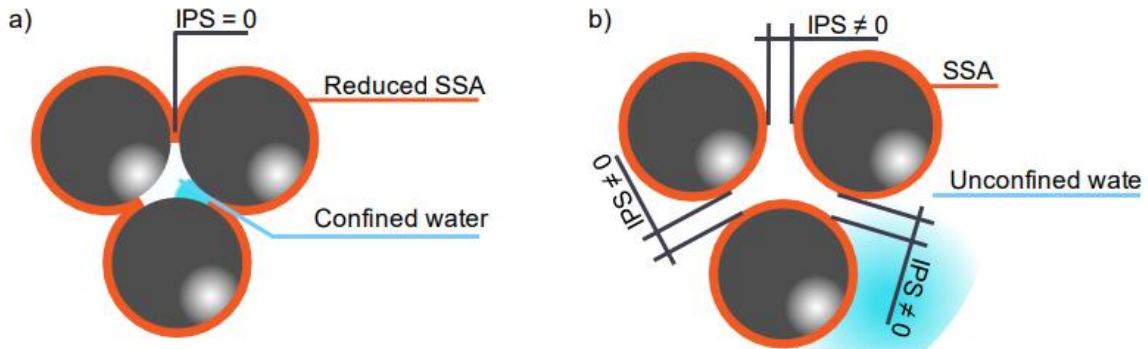


Figure 9 - Interparticle Separation Distance (IPS):

a) Particles agglomerated with IPS = 0; b) Particles deagglomerated with IPS ≠ 0

## 2.3 RECYCLED CONCRETE AGGREGATES

Recycled concrete aggregates (RCA) have accumulated significant attention in recent years as a sustainable alternative to conventional aggregates in construction. Typically classified into coarse (CRCA) and fine (FRCA) categories, RCA are derived from: a) concrete returned to the plant due to a surplus or non-compliance with site specifications and b) demolished concrete structures as a result of either: damaged concrete structures deemed unable to be rehabilitated, or concrete structures that no-longer comply with the current codes and standards, or concrete structures that has reached the end of its service life. Since aggregates make up 60% to 75% of the concrete's volume, it is important to take advantage of RCA's in the construction of new concrete as exploitation and transportation of new natural aggregates (NA) is a costly operation. Researchers throughout the past years have shown that through proper RCA preparation, characterization, mix proportioning, and accounting for the RCA's multi-phase character, the recycled concrete can achieve targeted mechanical properties and durability while remaining environmentally friendly [9] [10] [1].

In the literature, CRCA is described as a multiphase material consisting of natural aggregates (NA) with adhered residual mortar (RM). This composition results in a rough and porous microstructure, often containing micro-cracks. The proportion of RM varies based on factors such as the type and quality of the original virgin aggregate (OVA) and the characteristics of the RM itself. On the other hand, FRCA is characterized by fine granular material with significant amounts of residual cement paste (RCP) adhered to fine aggregate particles. This presence of RCP can affect various physical properties of FRCA, including specific gravity, porosity, and water absorption. Consequently, FRCA is often considered of lower quality compared to CRCA due to its higher RCP content [27] [28]. There are several available methods for mix designing concrete with RCA that have been further reviewed and developed in recent literature which are discussed in the following sections.

### 2.3.1 CRCA: DIRECT REPLACEMENT DESIGN METHOD

**Direct Replacement Method (DRM):** The DRM method is considered one of the very first attempts to mix proportion concrete with the use of RCA and can as indicated by the name of the method, the method is to partially replace natural aggregates (NA) with RCA without accounting for the difference in the microstructure such as presence of RM on the RCA's. There are two DRM approaches which are: direct weight replacement (DWR) and direct volume replacement (DVR). Both approaches yield very similar results, if not the same results as the RCA in these methods is treated as single phase material where the RM within the recycled particles is not accounted for which goes against the definition of CRCA's and FRCA's stated above that they are multiphase

materials. When applying the DRM method in concrete mix design, the amount of coarse aggregates (CA) which comprises of the OVA and the added NA is lower than the NA in a conventional mix since the weight of the OVA includes RM which is not considered and consequently RCA mixtures using the DRM method yield inferior fresh and hardened state behaviours in comparison to CC mixes made with natural aggregates [29].

### 2.3.2 CRCA: EQUIVALENT MORTAR VOLUME DESIGN METHOD

**Equivalent Mortar Volume Method (EMV):** The EMV method is the first proposed method that considers RCA's multi-phase nature which considers and adjusts the binder content within the mix based on existing RM content on the RCA particles. The governing principle behind the EMV method is that the total design volumes of mortar and coarse aggregate should always remain the same regardless of whether the mortar is already hardened (RM) or fresh. Fathifazl et al. [1] has shown that although the use of the EMV method considers RCA's multi-phase nature, the mix will result in having a larger aggregates volume when compared to conventional concrete mixes and the reason for this is that RM behaves as an aggregate in the fresh state whereas is a mortar in the hardened state. Due to this phenomenon, the fresh state behavior of RCA mixes using the EMV method are undesirable as they result in high consistency, low flowability, and unreliable rheological behavior. The hardened state behavior on the other hand has performed as expected and designed showing that there is potential for use of RCA's in structural concrete as long as the fresh state behavior can be improved. Similar to conventional concrete, there are approaches to improve the fresh state by adding more cement or introducing chemical admixtures but those approaches go against the overall goal of producing a more sustainable mix. The concept of the EMV method is expressed in the equation below which shows that the volume of air, fine aggregates, cement, and water for natural aggregate concrete must be equal to the volume of the residual mortar, fine aggregates, cement, water, and air for RCA mixes.

$$V_{air} + V_{FA}^{NAC} + V_{Cement}^{NAC} + V_{Water}^{NAC} = V_{RM}^{RCA} + V_{FA}^{RCA} + V_{Cement}^{RCA} + V_{Water}^{RCA} + V_{air}$$

The same concept expressed in the above equation is schematically shown in figure 10 below.

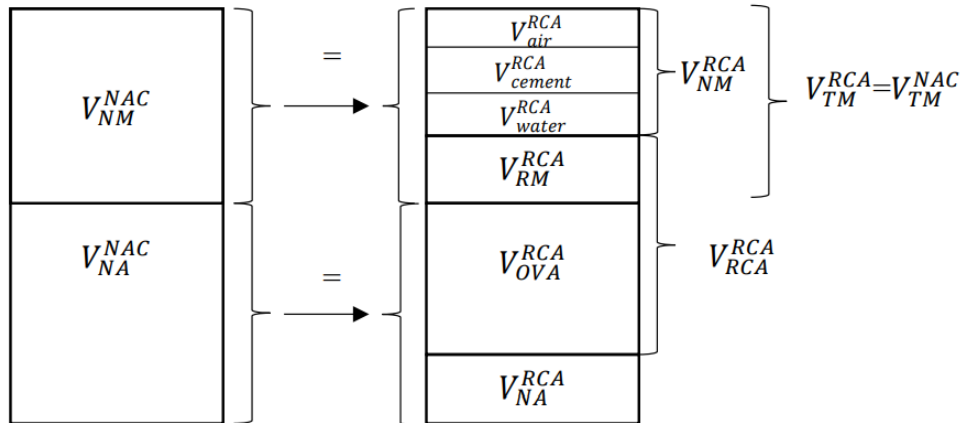


Figure 10 - Schematic of EMV Method Design Principle

where  $V^{NAC}$  refers to the volume of a constituent within the normal aggregate concrete and  $V^{RCA}$  is the volume of a constituent within the RCA concrete. Subscripts on both  $V^{NAC}$  and  $V^{RCA}$  denote each of the constituents. FA and RM represent the fine aggregates and residual mortar respectively, while subscripts TM and NM refer to the proportions of Total Mortar and New Mortar in the designs.

Using this method, the designer can specify the volumetric ratio of NA in the RCA concrete to aggregate in the control mix with, denoted by R:

$$R = \frac{V_{NA}^{RCA}}{V_{NA}^{NAC}}$$

Where  $V_{NA}^{RCA}$  and  $V_{NA}^{NAC}$  are the volumes of natural aggregate in the RCA mix and in the control mix design, respectively. With this relationship,  $R = 0$  corresponds to a mix that does not contain any natural aggregates, and  $R = 1$  is the control mix, or no RCA. This factor R is then used to calculate the required volume of mortar in the RCA mix design. The required masses of water, cement and fine aggregates are scaled down accordingly based on the reduced volume of mortar.

### 2.3.3 CRCA: MODIFIED EQUIVALENT MORTAR VOLUME DESIGN METHOD

**Modified Equivalent Mortar Volume Method (EMV-mod):** The modified EMV method was developed to improve the performance of RCA mixes in the fresh state since low cement content mixes designed with the conventional EMV method were found to have issues with workability with the new mortar being unable to fully embed the coarse aggregates. There are two main design changes to the EMV method which are: 1) Use of a revised Abrams law specific to RCA developed by Hayles [9] and 2) Addition of a new factor “cement to sand mass ratio” to select revised amount of cement in the new RCA mix (developed by Hayles [9]). The results from Hayles research on the use of RCA using the EMV method showed that RCA at all the w/c ratios tested were lower than the expected values, likely due to the different microstructure and crack pattern found for RCA mixes and for this reason the same Abrams law could not be directly applied to RCA mixtures. The EMV method is also restricted in the approach that the new mortar is proportioned as the ratio of sand and new cement in the mortar needs to match the ratio of the control mix, this is why the modified EMV method calculates the required weights of fine aggregate and cement as a function of the desired ratio of the specific volumes of cement and sand. By doing this, the designer can specify the value of the “cement to sand mass ratio” to achieve a workable mix for a given application. The combination of the above design changes further improves the EMV method in the fresh and hardened state but does not improve the cement reduction and sustainability of mixes as the PC content is normally increased for a given targeted strength when compared to both CC and EMV-designed mixes [9].

### 2.3.4 CRCA: EQUIVALENT VOLUME DESIGN METHOD

**Equivalent Volume Method (EV):** The equivalent volume method is currently the latest RCA mix design method that was developed to further improve the EMV and modified EMV methods. There were two main challenges that the EV method was targeting to resolve which are the fresh state performance and further reduction of the PC amounts used while still maintaining favorable fresh and hardened state properties. The key difference between the EMV method and the EV method is that that EV is designed with the assumption that the RCA mix is based on a companion CC mixture having the same amount (in volume) of cement paste and aggregates as opposed of having the same amount of coarse aggregates and mortar as stated in the EMV method. This means that the EV method considers that the residual mortar (RM) is the sum of the of the residual paste and the residual fine aggregate which also means that that the total cement paste is the sum of the RP and the fresh paste (FP). The EV method is summarized into the following 4 conditions:

- I.  $V_{CP}^{RCA-Concrete} = V_{CP}^{CC}$
- II.  $V_{Ag}^{RCA-Concrete} = V_{Ag}^{CC}$
- III.  $V_{CP}^{RCA-Concrete} = V_{RP}^{RCA-Concrete} + V_{FP}^{RCA-Concrete}$
- IV.  $V_{TA}^{RCA-Concrete} = V_{OVA}^{RCA-Concrete} + V_{NA}^{RCA-Concrete}$

Where:

$V_{CP}^{RCA-Concrete}$	Total paste volume in RCA concrete
$V_{CP}^{CC}$	Cement Paste in Conventional Concrete Mix
$V_{Ag}^{RCA-Concrete}$	Total volume of coarse and fine aggregates in the RCA concrete which is also the sum of the volumes of new aggregate (NA: coarse and fine) and the original virgin aggregate (OVA: coarse and fine) contained in RCA
$V_{Ag}^{CC}$	Coarse & Fine Aggregates Volume in Conventional Concrete Mix
$V_{RP}^{RCA-Concrete}$	Residual Paste Volume in RCA Concrete
$V_{FP}^{RCA-Concrete}$	Fresh Paste Volume in RCA Concrete
$V_{TA}^{RCA-Concrete}$	Total Aggregate volume in the mix – OVA & NA
$V_{OVA}^{RCA-Concrete}$	Original Virgin Aggregate (coarse and fine) volume in the RCA concrete
$V_{NA}^{RCA-Concrete}$	New aggregate (NA) (coarse and fine) volume in the RCA concrete

Refer to figure 11 for a schematic showing a comparison in the proportions between RCA using the EV method and conventional concrete.

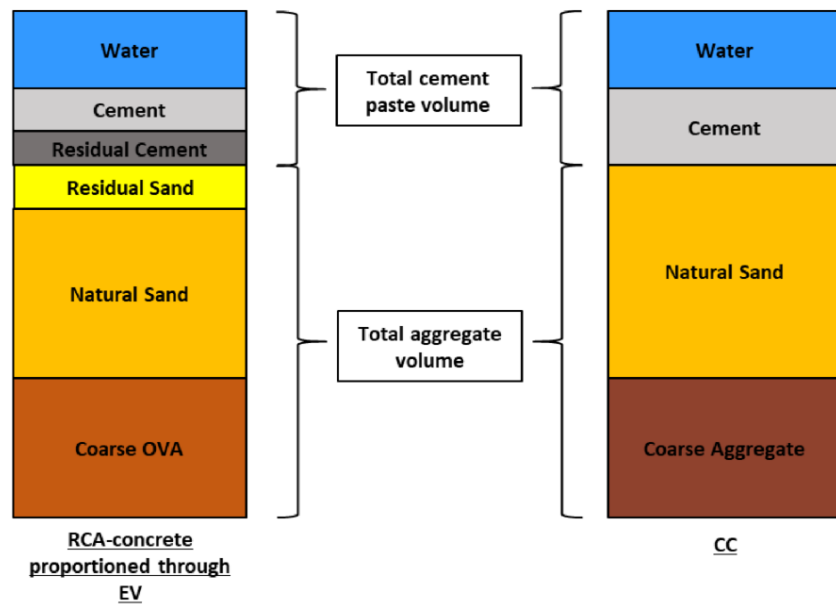


Figure 11 - Proportions in RCA Concrete Compared to Conventional Concrete

### 2.3.5 CRCA: COMPARISON BETWEEN CC, EMV, AND EV METHODS

To summarize the volumetric material comparison between CC mixes, the EMV method and the EV method, Refer to figure 12 below that illustrates the mix proportions for each method.

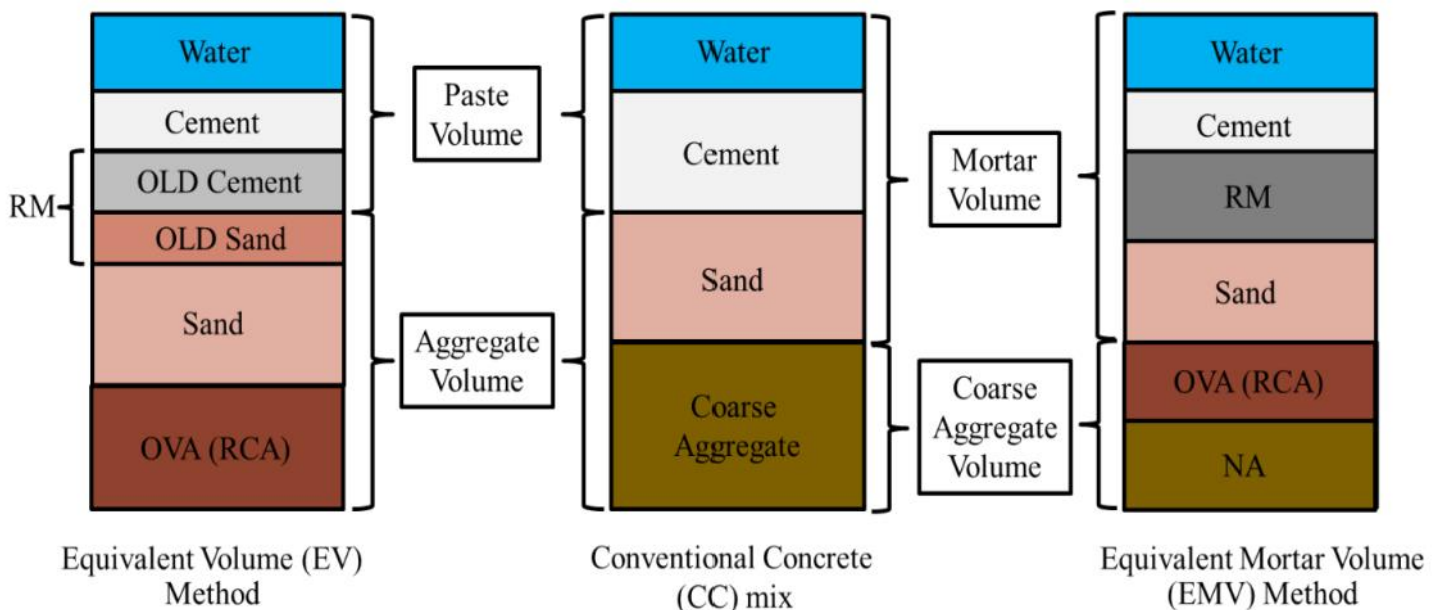
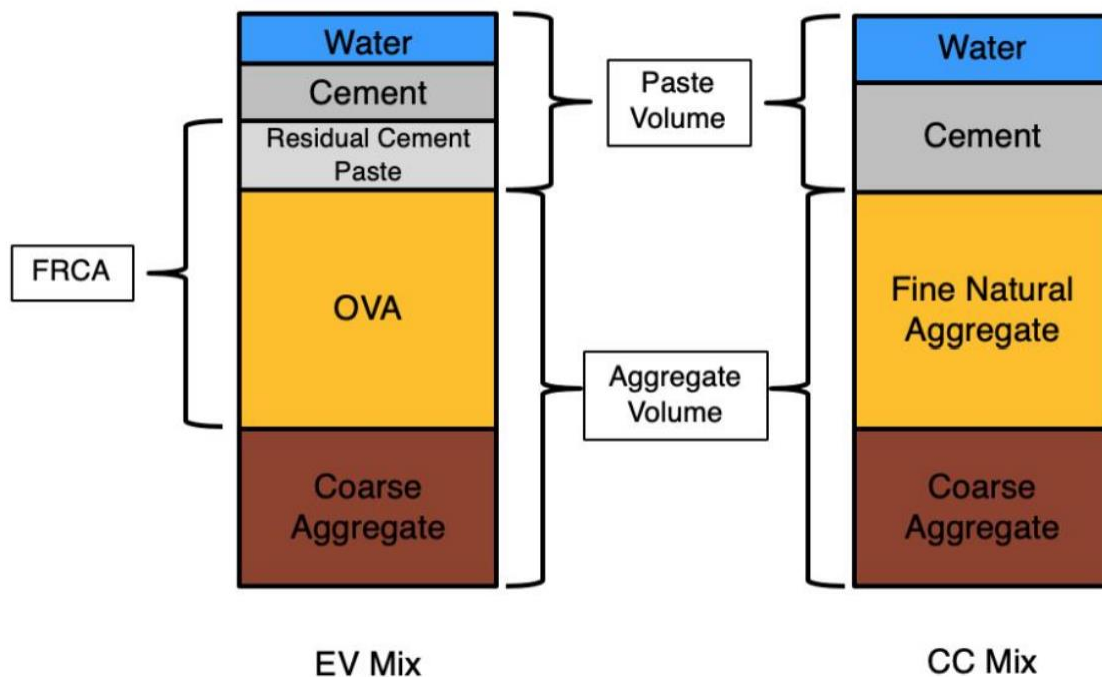


Figure 12 - Volumetric Material Comparison between RCA mixtures (designed with EMV and EV methods) and conventional concrete mixtures

### 2.3.6 FRCA: EQUIVALENT VOLUME DESIGN METHOD

All of the previously cited research was primarily focused on the use of CRCA and therefore research by Macedo [11] focused on the performance of concrete mixtures while incorporating fine recycled concrete aggregates (FRCA). Macedo evaluated the use of FRCA by employing multiple methods: 1) DRM approach (outlined in section 1.4.1), EV approach (outlined in section 1.4.4), and also a novel approach of combining EV and continuous PPM (Alfred model outlined in section 1.2.1). The EV principle with the use of FRCA remains the same as the one discussed with the use of CRCA: the FRCA mix is based on a companion conventional concrete (CC) mixture, having the same amount (in volume) of cement paste (CP) and aggregates. In other words, the total amount of cement paste in the EV mix is considered as the summation of the RCP plus the fresh paste added to the mix, while the total volume of aggregates is the volume of original virgin aggregates (OVA) plus the volume of natural aggregates (NA). The principle described above is best visualized in the schematic shown in figure 13 below which shows a comparison between the EV mix-designed concrete using FRCA and a companion CC mix.



*Figure 13 - EV Method Proportion of FRCA Concrete based on a CC Mix Design*

The main findings from Macedo's study were that the overall quality of FRCA material seems to be dependent on the manufacturing (i.e. crushing) method selected, the fresh state behavior through both EV and PPM methods is suitable for vibrated or pumped applications, and the hardened state properties were achieved through both the EV and PPM methods but not with the DRM method.

## 2.4 SUSTAINABILITY AND ECO-EFFICIENCY IN CONCRETE INDUSTRY

The link between climate change and CO<sub>2</sub> emissions is well-documented, with the PC industry identified as a significant contributor to the carbon footprint associated with civil construction. Furthermore, projections indicate a substantial increase in global PC production, expected to grow by 2.5 times from 2005 to 2050, predominantly in developing nations. In this context, enhancing the efficiency of PC utilization emerges as a crucial strategy for cutting CO<sub>2</sub> emissions. Adopting such measures could potentially lead to a 15% decrease in cement demand by 2050 [30]. Despite the lack of comprehensive investigation into this alternative, several preliminary strategies for reducing PC usage have been proposed, including: (a) employing high-range water reducers, also known as superplasticizers; (b) optimizing concrete mix designs through better particle packing or using Recycled Concrete Aggregate (RCA); (c) increasing concrete's compressive strength to reduce volume usage in projects; (d) use of SCM's and/or inert fillers as a partial replacement to PC; and (e) integrating the aforementioned approaches to create "green mixtures."

Each option presents its own set of challenges and benefits. For instance, while option (a) can lower PC consumption, the sustainability of superplasticizers is questionable, and their cost can be prohibitive. Option (c), focusing on enhanced compressive strength, may lead to higher expenses and the risk of over-engineering concrete structures, which is not desirable. Option (d), while effective is limited by material availability in different regions and is not able to maintain the level of demand required within the industry. On the other hand, option (b) stands out as the most viable and sustainable approach for advancing concrete mix designs, emphasizing the importance of innovation in creating environmentally friendly construction materials. This focus on sustainable development in the PC industry is pivotal for mitigating its environmental impact, highlighting the need for ongoing research and the implementation of eco-friendly practices in construction methodologies. To aid in providing a complete overview on sustainability and eco-efficiency within the concrete industry, the following topics are further discussed: life cycle analysis; use of SCM's and/or inert fillers; global warming potential; and binder/carbon intensity factors.

### 2.4.1 LIFE CYCLE ANALYSIS OF CONCRETE MIXTURES

Life Cycle Analysis (LCA) is a critical tool used in evaluating the total global warming potential and total cost of ownership of a project, material, or system over its entire life span. In the context of concrete mixtures, LCA plays a vital role in assessing the economic viability and environmental impacts of different concrete formulations by considering not only the initial costs but also the long-term maintenance, repair, and potential

environmental impacts. LCA is widely recognized for its ability to provide a comprehensive assessment of cost and environmental impact associated with a material or system throughout its life cycle. In construction, and particularly in concrete applications, LCA considers costs and GWP incurred during the production, installation, maintenance, repair, and end-of-life stages. The importance of LCA has grown with the increasing emphasis on sustainability, where long-term cost savings and environmental impacts are as significant as initial costs. All of the aforementioned mix design methodologies are focusing on developing eco-efficient mixtures while maintaining fresh and hardened state properties. It is important to review and understand the life cycle analysis of these concrete mixtures under the different stages of production. The four major steps in production of concrete are: 1) raw material production and transportation, 2) concrete production, 3) concrete transportation, and 4) concrete placement. The first phase accounts for 93.8% of the emission (332 kg CO<sub>2</sub>e/m<sup>3</sup>), wherein OPC (ordinary Portland cement) production and transportation accounts for approximately 82% of the total emission of the raw material phase [31]. Therefore, more than threequarters of emission resulting from conventional concrete mixtures productions is governed by OPC. Figure 14 shows a summary of the kg CO<sub>2</sub>e (carbon dioxide equivalent) per cubic meter of concrete produced after investigating CO<sub>2</sub> (carbon dioxide) emission in the concrete supply chain using a 40 MPa conventional concrete mix-design with 328 kg/m<sup>3</sup> of OPC and 1242, 781, and 190 kg/m<sup>3</sup> of coarse and fine aggregate and water content, respectively [31]. Several factors influence the outcomes of LCA's in concrete mixtures such as:

- 1) **Initial Material Costs:** The initial cost of raw materials and production can be higher for sustainable or high-performance mixtures, but these are often offset by lower life cycle costs.
- 2) **Environmental Impact Costs:** Incorporating sustainability into LCCA involves considering the costs related to the environmental impact, such as carbon emissions and energy consumption during production and transport.
- 3) **Maintenance Requirements:** The type and frequency of maintenance activities, such as sealing, resurfacing, and repairs, impact the overall costs. Mixtures that reduce these needs are generally more cost-effective in the long term. These requirements are typically determined throughout the use and testing of these mixtures. Maintenance requirements of new mixtures are considered uncertain as long term predictions need to be made.
- 4) **Durability and Longevity:** The expected lifespan of the concrete significantly affects life cycle costs. Mixtures that enhance durability reduce the frequency and cost of repairs.
- 5) **System Boundaries:** The inclusion or exclusion of specific life cycle stages (e.g., cradle-to-gate, cradle-to-grave) determines the comprehensiveness of the analysis. Refer to section 2.4.3 for more details.
- 6) **Data Quality / Temporal Factors:** The accuracy, completeness, and reliability of data for inputs and outputs across the life cycle stages can greatly influence the results. Also, changes over time, such as improvements in technology or variations in material sourcing, can alter the environmental impacts.

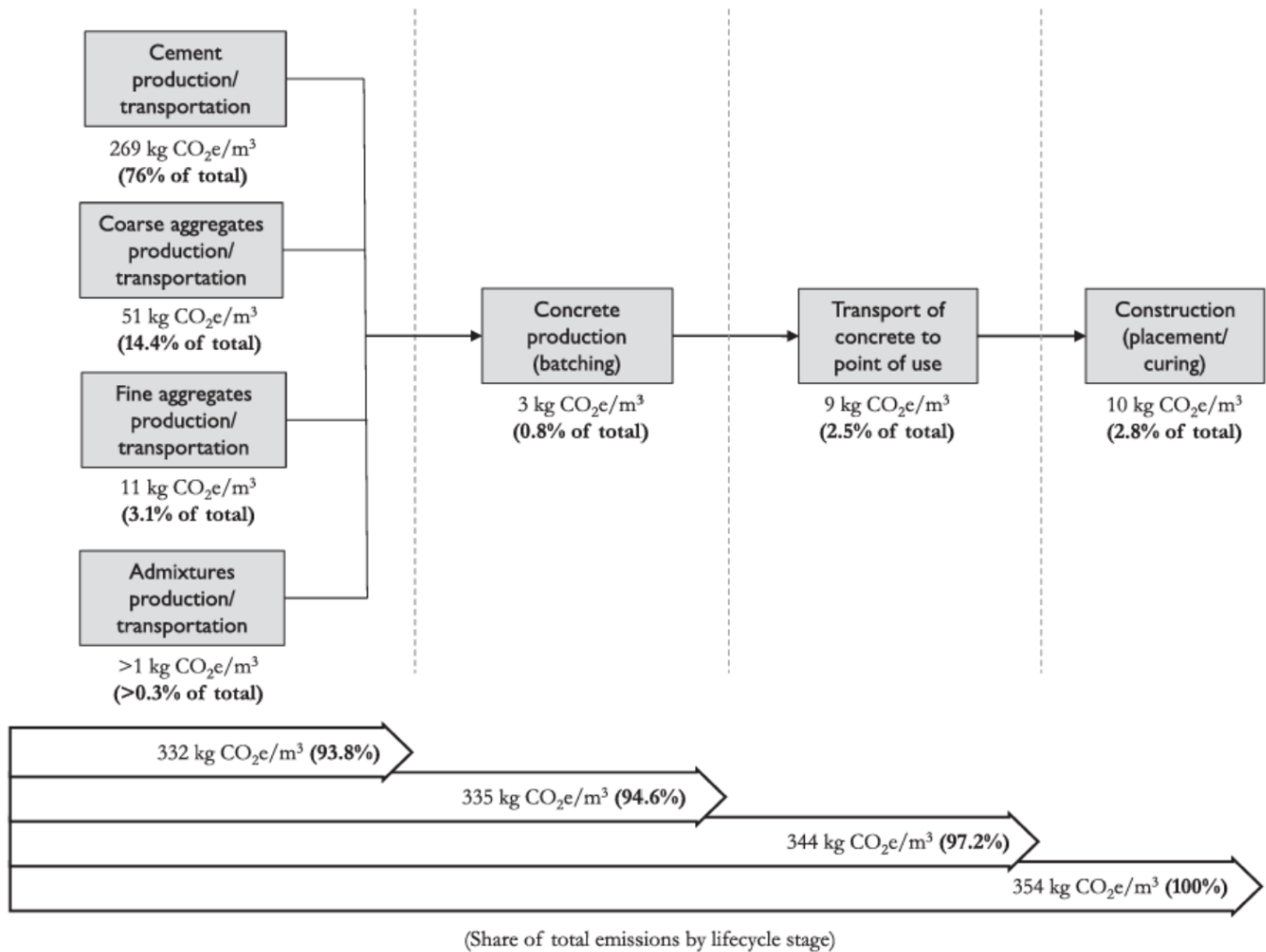
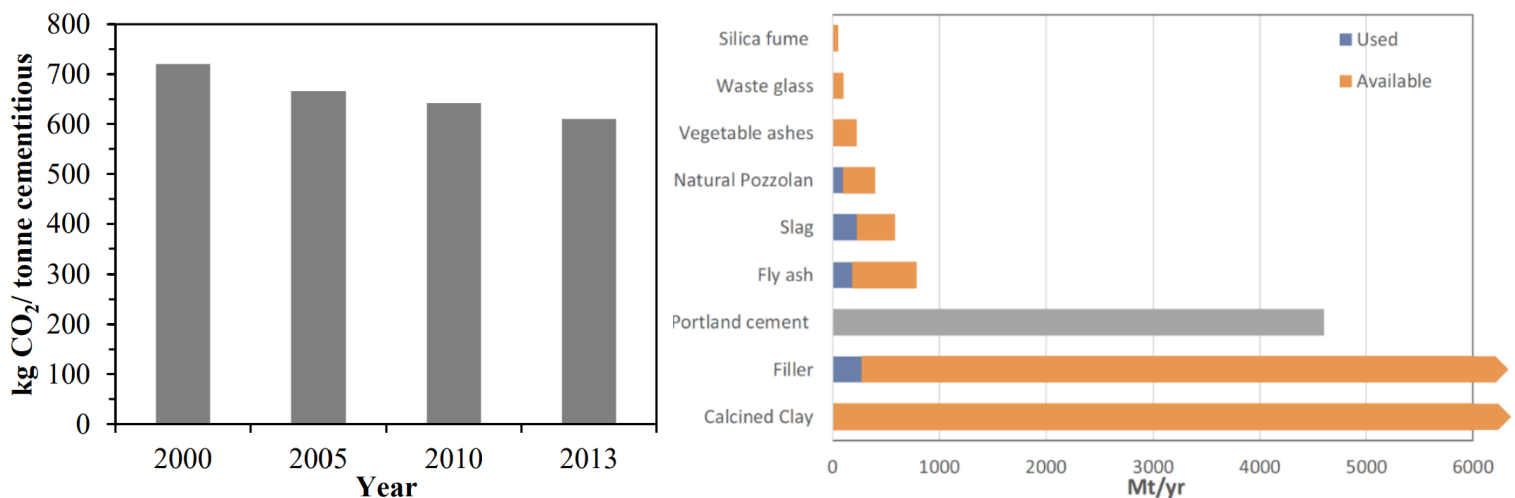


Figure 14 - Lifecycle analysis of concrete mixture developed with 40 MPa [31]

While the above provides a clear overview of the lifecycle of the concrete mixture, it only goes up to concrete placement, therefore further investigation is required in the post placement stages in order to provide a complete overview on the sustainability of these mixes as the definition of sustainability does not just address current eco-efficiency but also future reliability and performance. Ongoing research continues to refine LCA methodologies and expand their application to new and emerging concrete technologies, ensuring that this tool remains relevant in the quest for more cost-effective and sustainable construction practices.

## 2.4.2 USE OF SCM'S & INERT FILLERS

There are two main approaches used in practice within the industry for increasing concrete sustainability which are to replace PC with SCM's and/or inert fillers (e.g. limestone fillers). As outlined in section 1.1, SCM's are considered more eco-efficient than OPC since many are waste materials and/or industrial by-products [32]. The approach taken by the cement industry lately is that the use of SCM's is now being blended with the cement and therefore reducing the carbon footprint of the material prior to even arriving at the batching plant. Figure 15 on the left illustrates a notable trend: between 2000 and 2013, there was a 15% reduction in CO<sub>2</sub> emissions attributed to the utilization of blended cement [33]. Despite the potential to replace Ordinary Portland Cement (OPC) with up to 80% ground granulated blast furnace slag (GBFS), 70% fly ash, and 10% silica fume, traditional concrete formulations typically substitute supplementary cementitious materials (SCMs) for only 20% of OPC. This limitation primarily stems from the local scarcity of SCMs and their inadequate production capacity to meet the growing demand for OPC. Notably, Figure 15 on the right highlights that filler and calcined clay emerge as the primary alternatives for OPC, effectively addressing production challenges.



*Figure 15 – Left: CO<sub>2</sub> emissions of blended cement from 2000 to 2013 [33]; Right: Used and unused quantities of SCM and filler  
Substitutes for PC adapted from [35]*

Limestone filler (LF) stands out as the prevailing inert filler type, widely favored for its global availability, cost-effectiveness, and stability within cement paste. Its distinct advantages include its contribution to improved fresh-state properties owing to its shape and the flexibility to produce it in various particle size distributions (PSD) [34]. Typically, limestone fillers replace around 20% of the cement content, although certain standards, such as those in Europe and South Africa, permit replacement ratios of up to 35% [35] [36]. Recent research by de Grazia has demonstrated promising outcomes with replacement levels reaching up to 50% which

demonstrates that this should be further review and incorporated into LCC mix designs [37]. With an annual production volume of approximately 6,000 million tons as shown in figure 15 on the right side, fillers significantly surpass Portland cement output, underscoring their substantial presence in the construction industry [35]. Lothenbach et al. [38] conducted a comprehensive assessment of limestone fillers' impact on OPC hydration, highlighting their finely tuned PSD as a key factor augmenting cement hydration. This emphasis on PSD underscores a shift in focus from the chemical or physical interactions within the system to the mechanical properties influenced by filler characteristics. Fillers are classified into two categories: "replacement fillers", which share the same PSD as cement, and "performance fillers," characterized by a PSD lower than that of cement. To summarize, the main reasons to use LF as a replacement for cement are:

- 1) By-products sourced from aggregate quarries offer an economically viable and sustainable option for civil construction projects. These materials, often overlooked, present an opportunity to reduce waste and promote environmental responsibility within the construction industry [37].
- 2) There are significant ecological advantages associated with the use of these materials, primarily stemming from their role in curbing CO<sub>2</sub> emissions when compared to the production of OPC. Studies have consistently shown a marked reduction in carbon footprint, aligning with global efforts to mitigate climate change [39]
- 3) These materials boast a diverse range of particle size distributions (PSD) and are characterized by their spherical particle morphology. This unique composition not only enhances the fresh-state performance of cementitious mixtures but also contributes to improved workability and cohesion [34].
- 4) The addition of these materials has been observed to positively impact the rheological behavior of cementitious materials, including cement paste, mortar, and concrete produced with OPC. This phenomenon, known as the dilution effect, involves a reduction in OPC particle concentration while maintaining consistent water content. As a result, the mixture exhibits improved flow properties and reduced viscosity, facilitating easier placement and compaction [40].
- 5) Incorporating these materials into concrete formulations leads to enhancements in the material's microstructure, characterized by reduced porosity and shrinkage. These improvements not only bolster mechanical strength but also enhance durability-related properties, particularly those associated with the transport of harmful agents such as moisture and aggressive chemicals. Consequently, concrete structures fortified with these materials exhibit increased resistance to deterioration, prolonging their service life and reducing maintenance costs [39] [41].

### 2.4.3 GLOBAL WARMING POTENTIAL (GWP)

Assessing concrete eco-efficiency is as critical as reduction of the cement content to fairly and accurately compare the carbon footprint of each concrete mix design. The global warming potential (GWP) is a measure of how much energy one tonne of a gas will absorb over a given time period in comparison to one tonne of carbon dioxide emissions (CO<sub>2</sub>) [42]. In terms of concrete production, GWP can be translated into the total CO<sub>2</sub> emissions (in mass) per unit volume of concrete, and can also be calculated by the following equation [43]:

$$GWP = \sum_{i=1}^n m_i * g_i$$

where  $m_i$  is the mass of concrete ingredient (i) per unit volume of concrete and  $g_i$  is the e-CO<sub>2</sub> per unit mass of concrete ingredient (i). GWP is an important parameter that is typically the output of a life cycle analysis (LCA) and LCA tools are becoming very common and publicly available in the cement and concrete industry to support professional and research work. The publicly available LCA softwares are: 1) Slag Cement Association (SCA) LCA calculator [44]; 2) OpenConcrete [45]; 3) ZGF Concrete [46]; 4) GCCA EPD Tool [47] ; 5) GreenConcrete LCA Webtool [48]; 6) SimaPro [49]; 7) Ecoinvent 3 [50]. Each of these databases provides GWP (i.e., kg CO<sub>2</sub>eq/kg of material) of each concrete ingredient used to calculate the total GWP of concrete under different boundaries. In order to ensure that the GWP evaluation is accurate and comparable from one software to the other, it is important to set a boundary for the lifecycle of the material and these boundaries typically follow euopean standards as illustrated in table 3.

*Table 3 - Life cycle stages classification of building materials based on European standards [49]*

LCA boundaries		Life cycle stages/LCA information modules		Life cycle stage designation and description
Cradle to cradle	Cradle to grave	Cradle to gate	Product stage (A1-A3)	Raw material extraction and processing, processing of secondary material input (A1); Transport to the manufacturer(A2); Manufacturing (A3)
		Gate to grave	Construction process stage (A4-A5)	Transport to the building site (A4); Installation into the building (A5);
		Use stage - information modules related to the building fabric (B1-B5)	Use or application of the installed product (B1); Maintenance (B2); Repair (B3); Replacement (B4); Refurbishment (B5);	
		Use stage - information modules related to the operation of the building (B6-B7)	Operational energy use (B6); Operational water use (B7)	
		End-of-life stage (C1-C4)	De-construction, demolition (C1); Transport to waste processing (C2); Waste processing for reuse, recovery and/or recycling (3R) (C3); Disposal (C4)	
		Benefits and loads beyond the system boundary (D)	Reuse, recovery and/or recycling (3R) potentials (D)	

Witte et. al. completed a comparison of the first 5 LCA tools stated above and summarized the findings on the software's built-in features in a table format as shown in table 4 [51]. Based on the findings from Witte [51], the most suitable softwares to be used for evaluation of GWP for this work were GCCA (global cement and concrete association) & SCA (slag cement association). The primary reason for the use of GCCA & SCA tools over the other

tools is that they are the only two tools that incorporate the use of recycled aggregates as shown in Table 4. Since one of the main concrete materials used in this study is recycled concrete aggregates, it was essential to ensure that the LCA tools account for the residual mortar as well as the cost/environmental impact with recycling of the aggregates from their original use whether returned or re-used.

*Table 4 - Comparison of various publicly available LCA tools and their built-in features*

Features	LCA Tools				
	OpenConcrete	GCCA	SCA	Green Concrete	ZGF
Region customization	✓	✓	✓	✓	✓
Admixtures	✓	✓	✓	✓	
Transportation distance	✓	✓		✓	✓
Cement type customization (e.g. Type I vs Type II)	✓	✓	✓	✓	
Electricity mix customization	✓	✓		✓	
Full building impact estimation			✓		✓
Cradle-to-grave option		✓			✓
Considers steel reinforcement		✓			✓
Cement technology methods				✓	
Recycled Aggregates		✓	✓		

The use of Global Cement and Concrete Association (GCCA) Life Cycle Assessment (LCA) tool and the Slag Cement Association (SCA) LCA tool have a very similar purpose, and both comply with internationally recognized standards, such as ISO 14040 and ISO 14044, ensuring that the LCAs they produce are credible and comparable. Both tools evaluate similar environmental impact categories, such as global warming potential (GWP), energy consumption, and resource depletion, and they are used to inform decisions in product development, sustainability initiatives, and environmental reporting within the cement and concrete industries. Additionally, both tools require detailed input data related to raw materials, manufacturing processes, energy consumption, and transportation [51]. There are some key differences between the GCCA & SCA LCA tools:

### 1. Focus and Specialization:

- **GCCA Tool:** The GCCA tool is broader in scope, covering various types of cement, concrete, and reinforced concrete products. It is designed for a global audience and includes a wide range of concrete-related products.
- **SCA Tool:** The SCA tool is primarily focused on the north American market specialized for slag cement, focusing on the environmental benefits of incorporating slag cement into concrete mixtures, such as reducing CO<sub>2</sub> emissions.

### 2. Database and Default Values:

- **GCCA Tool:** Likely integrates a broader set of data from global databases as it targets a wide range of users, accommodating various types of cement and concrete products.

- **SCA Tool:** Geared towards companies and stakeholders involved in the production and use of slag cement, with a particular emphasis on promoting the environmental benefits of slag cement as an SCM material.

### 3. Customization and Flexibility:

- **GCCA Tool:** Provides flexibility to assess a variety of concrete mixtures and scenarios, accommodating different product configurations and life cycle stages.
- **SCA Tool:** May offer more specific tools or presets tailored to slag cement applications, focusing on scenarios where slag cement is a key component.

The GCCA LCA tool is a comprehensive and globally applicable tool for assessing the environmental impacts of various cement and concrete products. In contrast, the SCA LCA tool is specialized for slag cement, with a focus on North American applications and the environmental advantages of using slag cement. Both tools are vital for promoting sustainability in the cement and concrete industries, but they serve different purposes and audiences based on their scope and focus.

The GCCA & SCA tools are used by a wide range of stakeholders in the cement and concrete industry for various applications, including:

- **Product Development:** Manufacturers use the tool to evaluate the environmental performance of new cement and concrete formulations, helping them develop more sustainable products.
- **Design and Specification:** Architects and engineers use the tool to assess the environmental impact of different material choices and design options, enabling them to specify more sustainable building materials.
- **Regulatory and Certification Compliance:** The tool helps companies demonstrate compliance with environmental regulations and obtain sustainability certifications, such as LEED (Leadership in Energy and Environmental Design) and other green building standards.
- **Corporate Sustainability Reporting:** Companies use the tool to generate data for sustainability reports, helping them communicate their environmental performance to stakeholders, including customers, investors, and regulators.

Looking forward, the GCCA & SCA plan to continue enhancing their tools by incorporating new data, improving its user interface, and expanding its applicability to emerging materials and technologies. The GCCA & SCA are also working on integrating the LCA tool with other sustainability initiatives, such as carbon footprint calculators and circular economy frameworks, to provide a more holistic approach to sustainability assessment.

## 2.4.4 BINDER & CARBON INTENSITY (BI & CI FACTORS)

Damineli developed two performance indicators to estimate the binder and carbon dioxide efficiency which are defined as amount of binder or carbon dioxide required to obtain one desired unit of concrete [6]. The most common binder efficiency used is a function of the amount of Portland cement used for conventional concrete in kg/m<sup>3</sup> to obtain 1MPa of compressive strength at a given time such as 28 days. There are several advantages of using the *bi factor*, from being a simple concept to present a familiar outcome that once benchmarked, may be use for comparison with similar concrete families to assess the eco-efficiency of a given mix:

$$bi = \frac{B}{CS}$$

Where, *bi* is the binder intensity (in kg/m<sup>3</sup> x MPa<sup>-1</sup>), *B* is the binder amount (in kg/m<sup>3</sup>) and *CS* is the compressive strength in MPa. The CO<sub>2</sub> intensity similar to the binder intensity is a performance indicator to understand eco-efficiency of concrete. In the past, eco-efficiency was measured based on the amount of CO<sub>2</sub> emitted but this assessment would have not taken into account the different performance of differences concrete mixes. There may be difference concrete mixes that have different performance levels with the same amount of CO<sub>2</sub> emissions, and therefore the concrete mixes with better performance are comparatively more efficient. In order to include the concrete performance in the evaluation of the eco-efficiency, the CO<sub>2</sub> intensity factor was developed using the following equation where *C* is the total CO<sub>2</sub> emission in kg/m<sup>3</sup> generated by the production and transportation of all concrete material (from prediction models) and *CS* is the compressive strength in MPa at 28 days [6].

$$Ci = \frac{C}{CS}$$

As shown in the left graph of figure 16, a plot of the binder intensity vs the compressive strength is shown with results obtained from brazil in green and internationally in red. As shown on the left graph of figure 16, the higher the compressive strength, the lower the *bi* factor which shows that high strength concrete mixtures implicitly have lower binder intensities (lower carbon footprint). However, conventional concrete mixtures ranging from 20MPa to 40MPa have higher binder intensity factors and therefore the main focus of this research program is for these concrete mixtures. The second most common performance indicator studied by damineli in 2010 was the carbon intensity vs compressive strength as shown on the right graph of figure 16 which is evaluated as the total amount of CO<sub>2</sub> emissions generated by the production and transportation of concrete material to achieve 1MPa of compressive strength [6]. This index presents a relation between the concrete's environmental impact in the form of CO<sub>2</sub> emissions and concrete performance. The higher the carbon index, the

lower the eco-efficiency of the concrete and similar to the binder intensity factor, the higher the compressive strength, the lower the carbon intensity and consequently higher eco-efficiency [30].

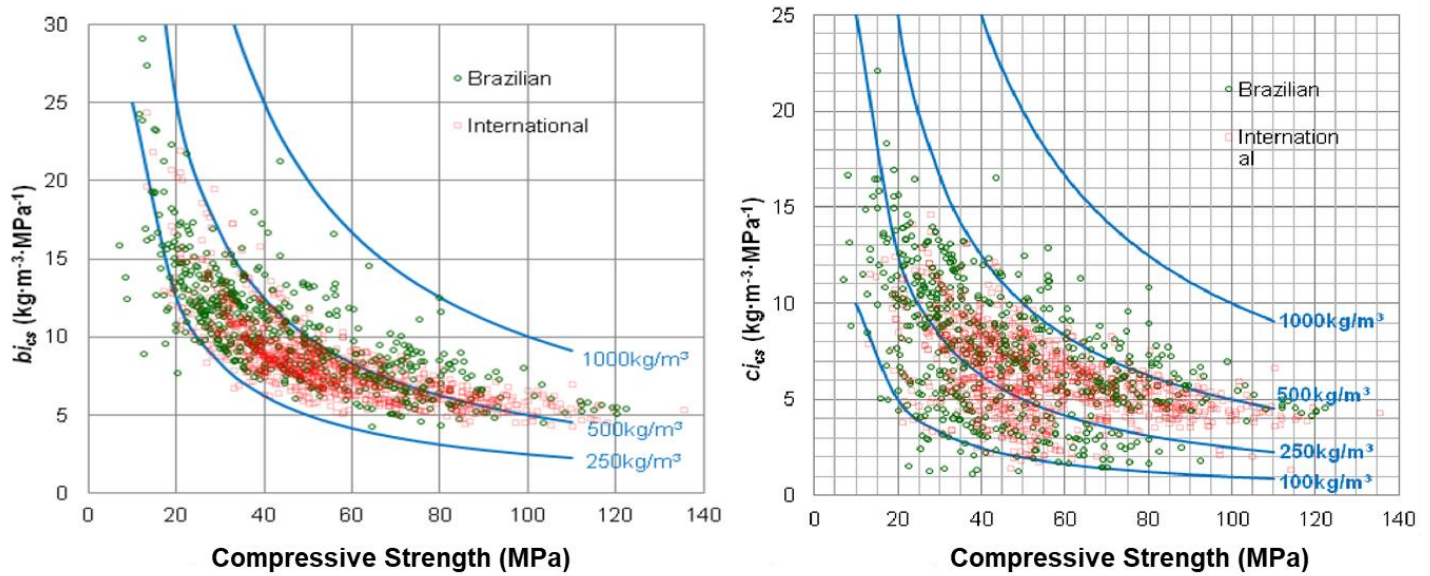


Figure 16 - Left Graph: Binder Intensity vs Compressive Strength, Right Graph: CO<sub>2</sub> Intensity vs Compressive Strength [3]

## 2.4.5 INTEGRATED STRENGTH ECO-EFFICIENCY (I-SEE) COEFFICIENT

Witte et. al. integrated strength ( $f'c$ ) and GWP (Kg CO<sub>2eq</sub>/m<sup>3</sup>) into a combined coefficient defined as Integrated Strength Eco-Efficiency (I-SEE). The I-SEE coefficient is the inverse of the carbon intensity factor outlined in section 1.5.4 and since GWP is in the denominator, the I-SEE value increases with the increase in eco-efficiency. Both I-SEE and Ci provide the same trend but I-SEE provides a larger spread in between the mixes. The below equation shows how I-SEE is calculated where  $f'c$  is the pure compressive strength and GWP is the global warming potential in Kg CO<sub>2eq</sub>/m<sup>3</sup>.

$$I - SEE = \frac{f'c}{GWP} * 100$$

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## CHAPTER 3: Influence of Sustainable Concrete Mix Designs on Costs & GWP

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**Shammeh. S.A.<sup>a</sup>, Sanchez L.F. M.<sup>b</sup>**

(a) MAsc Student – University of Ottawa

(b) Prof. Dr. – University of Ottawa  
Department of Civil Engineering

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### 3.1 SCOPE OF THE WORK

The research program was developed to address and fill a gap within the industry body of knowledge on the influence of sustainable concrete mix designs on overall cost and global warming potential. The three pillars of sustainability are Environmental, Social, and Economical. Researchers around the world have focused on the environmental and social implications of these mix designs by evaluating their fresh and hardened state properties but little to no research is present on their economical impact and therefore the aim of this study is to provide cost & GWP evaluation as a first step to a complete life cycle cost analysis. Decision makers throughout the world are always looking for quantitative data to help evaluate how to further improve their work and within concrete research the focus has already been on the overall performance of sustainable mix designs and not the cost implications. This study aims to analyze and quantify the cost and global warming potential of sustainable concrete mix designs through the use of PPM's, RCA, and MP's and compare them to standard industry used mix designs (conventional CSA/ACI Mixes and SCM Mix designs). Market research through collaboration with multiple concrete suppliers was completed to establish baseline pricing for conventional concrete and industry standard for green concrete (SCM mixes) and all the data was broken down by component to provide the ability to evaluate the pricing of alternate sustainable concrete mix designs.

## 3.2 MATERIALS & METHODS

To evaluate the role of sustainable concrete in the reduction of costs and reduction of global warming potential, a total of eight (8) concrete mix design groups were selected to provide a comparison between a variety of sustainable materials and methods. These eight mix design groups are all part of the previously discussed mix design methods in section 5.1 and 5.2. To evaluate the cost and GWP for each of these mix designs, the mix components, quantities, design strength, and sources all need to be reviewed to ensure that the pricing and GWP is reflective of this information. In practice, there are five main parameters that drive the price for a mix which are: desired strength, consistency/workability, class, air content, and carbon footprint. From a concrete supplier's pricing perspective, higher strength, higher consistency, and lower carbon footprint result in higher cost whereas in reality, lower carbon footprint contributes to a reduction in cost. For the purposes of this study, the costs analysis will be a function of strength and carbon footprint as the consistency/workability, class, and air content are relatively the same between all the mixes. The following subsections will provide an overview of the mix proportions for each of the 8 mix design groups:

- **Group 1:** Conventional concrete used for control purposes
- **Group 2:** Industry Standard for Green Concrete through the use of SCM's
- **Group 3:** Concrete designed with PPM
- **Group 4:** PPM proportioned concrete with SCM's
- **Group 5:** Concrete design with MP
- **Group 6:** PPM/MP mix proportioned concrete
- **Group 7:** Recycled Concrete Aggregate mixtures
- **Group 8:** PPM mix proportioned RCA concrete

### 3.2.1 Group 1: Conventional Concrete Materials & Methods

A conventional concrete mix using the absolute volume method as per ACI-211 [52] was selected as the conventional concrete mix which will be used as a control mix to compare all the other mixes to. This mix design is the standard mix used within the industry for typical concrete applications. Below is a brief overview on the materials used within this mix:

- **Fine & Coarse Aggregates:** Natural Sand & Crushed Limestone respectively adjusted to WA & SG.
- **Cement:** CSA Type GU Portland Cement
- **Mix Proportions:** Refer to Table 5 for CC Mix Design.
- **Target Strength ( $f'c$ ) and w/c ratio:** 25MPa (w/c = 0.61); 35MPa (w/c = 0.47); 45MPa (w/c = 0.39)

*Table 5 - Group 1: ACI Mix Design*

Group Name	Mix #	Mix Name	Design f'c (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
1 (ACI)	1	(1): ACI: 314-25	25	314	0	0	783	1024	0	0	191	0	0
	2	(2): ACI: 370-35	35	370	0	0	783	1024	0	0	174	0	0
	3	(3): ACI: 424-45	45	424	0	0	783	1024	0	0	169	0	0

### 3.2.2 Group 2: SCM Materials and Methods

The current standard for green sustainable concrete within the industry is optimise the use of supplementary cementitious materials in each mix to provide the lowest volume of cement achievable without compromising strength, durability, workability or strength gain requirements. The use of SCM's replaces the cement content and therefore reducing the carbon footprint. The mix design method used is in accordance with CSA A23.1 which is the absolute volume method with 40% replacement of the cement with SCM's for 25MPa & 35MPa mixes. For 45-50MPa mixes, industry standard is to use 40% Type GU cement, 20% SF (Silica fume), and 40% Slag Type S. Below is a brief overview on the materials used within this mix:

- **Fine & Coarse Aggregates:** Natural Sand & Crushed Limestone respectively adjusted to WA & SG.
- **Cement:** CSA Type GU Portland Cement
- **SCM:** Slag Type S per ASTM C989 and CSA A23.5 ; Silica Fume as per ASTM C1240 and CSA A23.5
- **Mix Proportions:** Refer to Table 6 for SCM mix Design
- **Target Strength (f'c) & w/c ratio:** 25MPa (w/c = 0.61); 35MPa (w/c = 0.47); 45MPa (w/c = 0.39)

*Table 6 - Group 2: SCM Mix Design*

Group Name	Mix #	Mix Name	Design f'c (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
2 (SCM's)	4	(4): ACI-SCM-60-40-25	25	188	0	126	783	1024	0	0	191	0	0
	5	(5): ACI-SCM-60-40-35	35	222	0	148	783	1024	0	0	174	0	0
	6	(6): ACI-SCM-60-40-45	45	254	0	170	783	1024	0	0	169	0	0

### 3.2.3 Group 3: Concrete Designed with PPM Materials & Methods

Two types of PPM mix designs were selected for evaluation. The first was developed by Yousef et al. [7] which employs the Alfred continuous particle packing model (PPM) with three different distributions factors and this was considered as the standard PPM mix design for this evaluation. The second was developed by de Grazia [8] which employs the Alfred PPM with the introduction of fillers and also breaking the PSD curve into two parts to improve the fresh state behavior.

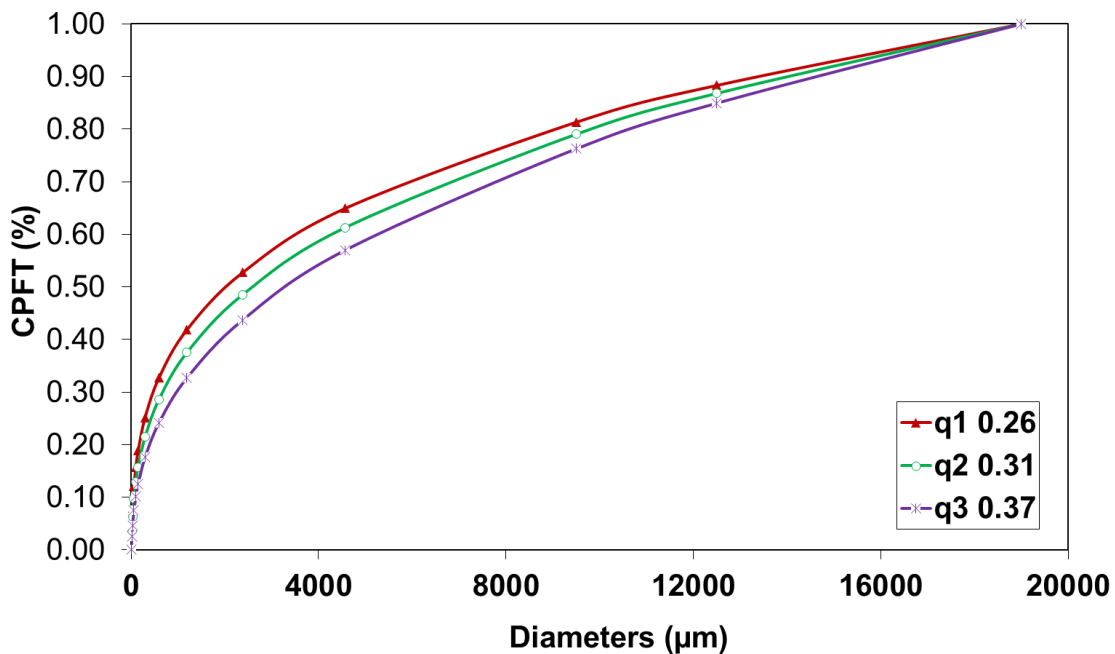
### 3.2.3.1 Standard PPM Materials & Methods

The standard PPM mix design employs Alfred continuous particle packing model [7] and three distributions factors were selected:  $q_1=0.26$ ,  $q_2 = 0.31$ , and  $q_3=0.37$  which represent low, moderate, and high particle packing distributions respectively. Below is a brief overview on the materials used within this mix:

- **Fine & Coarse Aggregates:** Natural Sand & Crushed Limestone respectively adjusted to WA & SG. The aggregates were distributed into eight different distinct particle size zones based on the CPFT calculation in the Alfred model. These eight zones include binder/fine material which is all material smaller than  $100\mu\text{m}$ , sand material which is all material from  $100\mu\text{m}$  to  $4750\mu\text{m}$ , and coarse material which is all material from  $4750\mu\text{m}$  to  $19000\mu\text{m}$ . All material was sieved according to ASTM standard C136 to obtain the required grading proportions for each mix.
- **Cement:** CSA Type GU Portland Cement (No SCM's or Chemical Admixtures were used)
- **Mix Proportions:** Refer to Table 7 for standard PPM Mix Design.
- **Target/Achieved Strength ( $f'_c$ ) and w/c ratio:** 25MPa ( $w/c = 0.61$ ) and 35MPa ( $w/c = 0.47$ )
- **Particle Size Distribution:** Refer to Figure 17 for the cumulative PSD of all three  $q$  factors.  $q_1=0.26$  was selected to provide the mixture with a high amount of fine particles;  $q_2=0.31$  was chosen to match the minimum binder amount required per ACI 302 and  $q_3=0.37$  was selected to provide maximum packing.

*Table 7 - Group 3A: Standard PPM Mix Design*

Group Name	Mix #	Mix Name	Design $f'_c$ (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
3A (Standard PPM)	7	(7): PPM $q_1 = 0.26$ (25MPa)	25	380	0	0	769	952	0	0	232	0	0
	8	(8): PPM $q_1 = 0.26$ (35MPa)	35	401	0	0	812	1005	0	0	188	0	0
	9	(9): PPM $q_2 = 0.31$ (25MPa)	25	326	0	0	770	1081	0	0	199	0	0
	10	(10): PPM $q_2 = 0.31$ (35MPa)	35	341	0	0	808	1133	0	0	160	0	0
	11	(11): PPM $q_3 = 0.37$ (25MPa)	25	266	0	0	760	1236	0	0	162	0	0
	12	(12): PPM $q_3 = 0.37$ (35MPa)	35	277	0	0	789	1283	0	0	130	0	0
	13	(13): PPM $q_3 = 0.37$ (35MPa) w/SP2	35	277	0	0	789	1283	0	0	130	5.5	0
	14	(14): PPM $q_3 = 0.37$ (35MPa) w/SP4	35	277	0	0	789	1283	0	0	130	11	0
	15	(15): PPM $q_3 = 0.37$ (35MPa) w/SP8	35	277	0	0	789	1283	0	0	130	22	0



*Figure 17 - Cumulative particle size distribution of the standard PPM mix proportioned designs*

### 3.2.3.2 Optimized PPM Materials & Methods

The optimized PPM mix design were designed using Alfred continuous PPM using a coefficient of distribution ( $q$ ) equal to 0.37 and were split into 2 phases:

- **Phase 1 (Mixes 11, 12, and 13):** Fillers were used as a PC partial replacement by percentage since the PSD of the fillers and PC were quite similar. Different binder content was selected for each mix while the water to fines (w/f) ratio was kept constant as 0.5 aiming for a desirable fresh state performance [8].
- **Phase 2 (Mixes 14, 15, and 16):** The PSD curve was split into two parts: the first from DS to 100 µm and the second from 100 µm to DL. Two distinct distribution factors were selected: 0.37 for the coarser particles (greater than 100 µm) and 0.21 for the finer particles (smaller than 100 µm). The lower coefficient factor (0.21) selected for the first part of the PSD (i.e. fines fraction) aimed to improve the fresh state properties of the mixture [8].

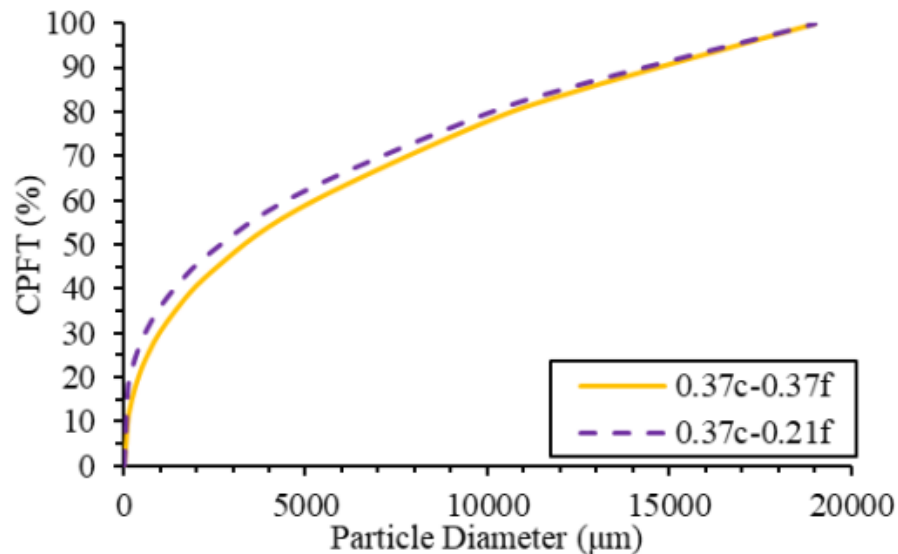
Below is a brief overview on the materials used within this mix:

- **Fine Aggregates:** Two types of sand – one natural sand with nominal maximum size (NMS) of 500 µm and another manufactured limestone sand with NMS of 4.75 mm.
- **Coarse Aggregates:** Limestone coarse aggregate (NMS of 19mm) from Sao Paulo, Brazil
- **Cement:** High early strength (type HE) PC from the Brazilian market (similar to ASTM C150 type III CP)
- **Filler:** Limestone Filler

- **Mix Proportions:** Refer to Table 8 for optimized PPM Mix Design.
- **Strength ( $f'c$ ) and w/c ratio:** No specific target strength was designed for. Mixes achieved strength results ranging from 43MPa to 70MPa. w/c ratios were kept consistent between phase 1 and phase 2 at 0.54, 0.61, and 0.80.
- **Particle Size Distribution:** Refer to figure 18 for CPFT vs particle size for phases 1 and 2.
- **Admixture:** A polycarboxylate-based high range water reducer was used to increase the flowability.

*Table 8 - Group 3B: Optimized PPM Mix Design*

Group Name	Mix #	Mix Name	Design $f_c$ (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
<b>3B</b> (Optimized PPM)	16	(16): OPPM - C261-0.37c-0.37f	65	261	0	0	777	1275	0	0	140	0	1.35
	17	(17): OPPM - C197-0.37c-0.37f	55	197	61	0	795	1304	0	0	120	0	1.31
	18	(18): OPPM - C149-0.37c-0.37f	43	149	104	0	797	1308	0	0	118	0	1.28
	19	(19): OPPM - C282-0.37c-0.21f	70	282	143	0	703	1153	0	0	152	0	2.03
	20	(20): OPPM - C214-0.37c-0.21f	55	214	212	0	721	1182	0	0	131	0	1.99
	21	(21): OPPM - C161-0.37c-0.21f	50	161	259	0	723	1186	0	0	128	0	1.95



*Figure 18 – Optimized PPM: CPFT vs Particle Size Distribution for Phase 1 & 2 Concrete Mixtures*

### 3.2.4 Group 4: PPM Proportioned Concrete with SCM's Materials & Methods

A combined PPM (Alfred model using  $q=0.37$ ) and SCM mix design was developed by [53] to show both of these approaches can work together to achieve a more eco-efficient mixture. Below is a brief overview on the materials used within this mix:

- **Fine & Coarse Aggregates:** Natural Sand & Crushed Limestone respectively adjusted to WA & SG.
- **Cement:** CSA Type GU Portland Cement
- **SCM:** Slag Type S ASTM C989 and CSA A23.5
- **Filler:** Limestone Filler
- **Mix Proportions:** Refer to Table 9 for mix design of PPM proportioned concrete with SCM's
- **Target/Achieved Strength ( $f'c$ ) and w/c ratio:** 35MPa ( $w/c = 0.47$ )

*Table 9 - Group 4: Combined Standard PPM & SCM Mix Design*

Group Name	Mix #	Mix Name	Design $f'c$ (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
4 (Combined PPM & SCM)	22	(22): PPM & SCM - C161 - $q=0.37$	35	161	0	85	1023	950	0	0	165	0	0
	23	(23): PPM & SCM - C152 - $q=0.37$	35	152	53	93	1023	950	0	0	165	0	0
	24	(24): PPM & SCM - C200 - $q=0.37$	35	200	0	106	1023	950	0	0	165	0	0
	25	(25): PPM & SCM - C190 - $q=0.37$	35	190	70	116	1023	950	0	0	165	0	0
	26	(26): PPM & SCM - C152 - $q=0.37$	35	152	0	80	1023	950	0	0	156	0	0
	27	(27): PPM & SCM - C187 - $q=0.37$	35	187	0	99	1023	950	0	0	154	0	0

### 3.2.5 Group 5: Concrete Designed with MP Materials & Methods

Three distinct mixes were mix proportioned using mobility parameters: IPS & MPT by [8] to show the influence of the amount of cement on the fresh and hardened state properties of LCC systems. These mixes targeted very low cement content compared to conventional concrete: 54 kg/m<sup>3</sup>, 159 kg/m<sup>3</sup>, and 260 kg/m<sup>3</sup>. This mix design did not consider or incorporate any other mix design techniques such as: PPM's, use of SCM's etc. but did incorporate two types of limestone fillers and also used two types of chemical admixtures. Below is a brief overview on the materials used within this mix:

- **Fine Aggregates:** Two types of sand – one natural sand with nominal maximum size (NMS) of 500  $\mu\text{m}$  and another manufactured limestone sand with NMS of 4.75 mm.
- **Coarse Aggregates:** Limestone coarse aggregate (NMS of 19mm) from Sao Paulo, Brazil
- **Cement:** High early strength (type HE) PC from the Brazilian market (similar to ASTM C150 type III CP)
- **Filler:** Two types of limestone fillers –
  - Performance Fillers: composed by particles smaller than PC
  - Replacement Fillers: composed by particles similar to PC.

- **Mix Proportions:** Refer to Table 10 for concrete designed with MP mix design
- **Strength (f'c) and w/c ratio:** No specific target strength was designed for. One of the goals of the mix design was to see the influence of the cement content on the hardened state properties.
- **Admixture:** Two types of chemical admixtures to guarantee an appropriate fresh state behavior –
  - a lignosulfonate-based mid-range plasticizer
  - a polycarboxylate-based superplasticizer

*Table 10 - Group 5: Mobility Parameters Mix Designs*

Group Name	Mix #	Mix Name	Design f'c (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
5 (Mobility Parameters)	28	(28): MP - C54	15	54	356	0	833	1059	0	0	115	2	2
	29	(29): MP - C159	45	159	244	0	820	1041	0	0	133	2	2
	30	(30): MP - C260	70	260	138	0	810	1029	0	0	146	2	2

### 3.2.6 Group 6: PPM/MP Mix Proportioned Concrete Materials & Methods

A combined PPM and MP mix design was developed by de Grazia [53]. The PPM model used was the continuous Alfred PPM model with a broken PSD curves as described as part of phase 2 of optimized PPM in section 4.4.3.2. After combining the FA, CA, Fillers, and Cement into one PSD curve, two q-factors were pre-selected to achieve the lowest system porosity. For the powder portion (from  $D_s$  to  $D_{\text{powder}}$   $\mu\text{m}$ ) a q-factor of 0.34 was selected, whereas a q-factor of 0.31 was found to be optimum on the aggregate portion. Control mixtures 31, 32, and 33 were developed without limestone filler addition, resulting in cement content of around 320 kg/m<sup>3</sup>, whereas the other nine mixtures (34 to 42) were developed with performance filler. To evaluate the impact of limestone filler and cement content on the mixtures, three ranges of cement content (250, 200, and 150 kg/m<sup>3</sup>) were selected. To achieve the target cement content, “replacement fillers” were added. Mobility parameters of each mix design were calculated to ensure that each mix maintains the same mobility parameter range. Below is a brief overview on the materials used within this mix:

- **Fine & Coarse Aggregates:** Natural Sand & Crushed Limestone respectively adjusted to WA & SG.
- **Cement:** CSA Type GU Portland Cement
- **Filler:** Two types of limestone fillers – Performance Fillers (composed by particles smaller than PC) and Replacement Fillers (composed by particles similar to PC)
- **Mix Proportions:** Refer to Table 11 for PPM/MP Mix Proportioned Concrete Mix Design
- **Target Strength (f'c) and w/c ratio:** 20MPa (w/c = 0.68), 25MPa (w/c = 0.61) and 30MPa (w/c = 0.52)
- **Admixture:** Two types of chemical admixtures to guarantee an appropriate fresh state behavior –
  - a polycarboxylate-based high-range water reducer
  - a lignosulfonate-based mid-range plasticizer

*Table 11 - Group 6: Combined PPM & MP Mix Designs*

Group Name	Mix #	Mix Name	Design f <sub>c</sub> (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
<b>6</b> (Combined PPM & MP)	31	(31): PPM-MP: 1H-311-0.68	28	311	0	0	1011	847	0	0	212	0	0
	32	(32): PPM-MP: 1M-319-0.60	32	320	0	0	1038	869	0	0	192	0	0
	33	(33): PPM-MP: 1L-328-0.52	38	328	0	0	1065	892	0	0	171	0	0
	34	(34): PPM-MP: 2H-250-0.68	30	250	64	0	1065	892	0	0	170	1.9	1.9
	35	(35): PPM-MP: 2M-250-0.60	34	250	71	0	1092	914	0	0	150	3.9	3.2
	36	(36): PPM-MP: 2L-250-0.52	45	250	78	0	1119	936	0	0	130	3.9	3.9
	37	(37): PPM-MP: 3H-200-0.83	25	200	109	0	1072	898	0	0	165	1.9	1.9
	38	(38): PPM-MP: 3M-200-0.74	31	200	115	0	1093	916	0	0	148	3.8	3.1
	39	(39): PPM-MP: 3L-200-0.64	32	200	120	0	1123	939	0	0	129	3.9	3.9
	40	(40): PPM-MP: 4H-150-1.09	18	150	151	0	1087	890	0	0	163	2.4	1.2
	41	(41): PPM-MP: 4M-150-0.97	21	150	158	0	1111	911	0	0	145	4.3	2.5
	42	(42): PPM-MP: 4L-150-0.84	27	150	164	0	1136	931	0	0	126	3.9	3.9

### 3.2.7 Group 7: RCA Mixture Materials & Methods

Four types of PPM mix designs were selected for evaluation each with different materials or methods. The first was tested by [9] using the EMV method by evaluating to sources of RCA at different replacement content. The second was developed by [9] which is a modified EMV approach that was previously discussed in section 1.4.3. The third was developed by [10] which employs the equivalent volume mix design method. The fourth mix design was developed by [11] showing the performance of FRCA under the EV method.

#### 3.2.7.1 Group 7A: Coarse RCA EMV Method Mix Design

The CRCA EMV Mix design method was developed by [1] and tested by [9] by obtaining two sources of RCA: 1) **RU** which refers to reused concrete material produced from waste collected from multiple demolition sites and 2) **RT** material returned to the concrete production facility and crushed on site to create the RCA. The EMV mix design method was proportioned with aggregate replacement contents of 50% and 100% RCA for the RU source; and 50% and 81.2% RCA for the RT source. There were concerns with the fresh state of the RU source RCA and therefore, the mix was distinguished into “A” and “B” mix designs. The “A” mix design follows the EMV method. The “B” mix design follows EMV but increases the cement content while maintaining the same w/c ratio to improve the fresh state behavior. Below is a brief overview on the materials used within this mix:

- **Fine Aggregates:** Natural sand
- **Coarse Aggregates:** Three types: NA, RU-RCA, RT-RCA (All Limestone in nature)
- **Cement:** CSA Type GU Portland Cement
- **Mix Proportions:** Refer to Table 12 for RCA EMV Mix Design
- **Target Strength (f<sub>c</sub>) and w/c ratio:** 25MPa (w/c = 0.61) and 35MPa (w/c = 0.47)

*Table 12 - Group 7A: RCA EMV Method Mix Design*

Group Name	Mix #	Mix Name	Design f <sub>c</sub> (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
7A (RCA EMV Method)	43	(43): RCA EMV: 0-NA-25	25	314	0	0	790	1029	0	0	192	0	0
	44	(44): RCA EMV: 50-RU-25	25	220	0	0	555	515	0	887	135	0	0
	45	(45): RCA EMV: 50-RT-25	25	264	0	0	665	509	0	697	162	0	0
	46	(46): RCA EMV: 81-RU-25A	25	162	0	0	405	193	0	1440	99	0	0
	47	(47): RCA EMV: 81-RU-25B	25	208	0	0	384	183	0	1367	127	0	0
	48	(48): RCA EMV: 100-RT-25	25	215	0	0	542	0	0	1380	132	0	0
	49	(49): RCA EMV: 0-NA-35	35	370	0	0	790	1029	0	0	174	0	0
	50	(50): RCA EMV: 50-RU-35	35	260	0	0	555	515	0	887	122	0	0
	51	(51): RCA EMV: 50-RT-35	35	312	0	0	666	515	0	690	147	0	0
	52	(52): RCA EMV: 81-RU-35A	35	191	0	0	408	193	0	1440	90	0	0
	53	(53): RCA EMV: 81-RU-35B	35	239	0	0	390	184	0	1375	113	0	0
	54	(54): RCA EMV: 100-RT-35	35	254	0	0	542	0	0	1380	119	0	0

### 3.2.7.2 Group 7B: Coarse RCA Modified EMV Method Mix Design

The CRCA modified EMV method was established by Hayles [9] as a two-step optimization from the basic CRCA EMV method. The first step was to revise abrams law to one that is more specific to RCA and second step was to introduce a new “cement to sand mass ratio”. Both of these steps were to improve the ability to predict the fresh and hardened state properties but do not improve the eco-efficiency. A control mix with a slightly higher cement content was selected as another strategy of increasing the workability of the concrete in the fresh state. Mixes 56 & 57 in table 13 below only include the first step of the optimization whereas mix 58 includes both steps of optimization. Below is a brief overview on the materials used within this mix:

- **Fine Aggregates:** Natural sand
- **Coarse Aggregates:** NA & RT
- **Cement:** CSA Type GU Portland Cement
- **Mix Proportions:** Refer to Table 13 for CRCA Modified EMV method Mix Design.
- **Target Strength (f<sub>c</sub>) and w/c ratio:** 35MPa (w/c = 0.47)

*Table 13 - Group 7B: CRCA Modified EMV Method Mix Design*

Group Name	Mix #	Mix Name	Design f <sub>c</sub> (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
7B (RCA EV-mod Method)	55	(55): RCA EMV-mod: 0-NA2-35	35	400	0	0	723	1056	0	0	180	0	0
	56	(56): RCA EMV-mod: 100-RTO-35A	35	277	0	0	614	0	0	1416	125	0	0
	57	(57): RCA EMV-mod: 100-RTO-35B	35	322	0	0	521	0	0	1416	191	0	0
	58	(58): RCA EMV-mod: 100-RTM-35	35	322	0	0	547	0	0	1416	135	0	0

### 3.2.7.3 Group 7C: Coarse RCA EV Method Mix Design

The CRCA EV method was established by Ahimoghadam [10] as an improvement to the fresh state performance compared to the EMV method especially when targeting low amounts of cement. EV is designed with the assumption that the RCA mix is based on a companion CC mixture having the same amount (in volume) of cement paste and aggregates as opposed of having the same amount of coarse aggregates and mortar as stated in the EMV. Three different CC mixtures were selected with three different compressive strengths to be used as a companion mixture for RCA's using the EV method. RCA was characterized and the RM was evaluated to perform the EV method. Specimens from the CC mixtures were jaw crushed to be used as RCA particles. RCA particles from the 25MPa CC mix were used to generate 25MPa RCA concrete and same concept was adopted for 35MPa and 45MPa mixes. All mix designs considered a 100% CRCA replacement therefore no NA was used in these mixes. Below is a brief overview on the materials used within this mix:

- **Fine Aggregates:** Natural sand
- **Coarse Aggregates:** Limestone; RCA Particles were jaw crushed from CC specimens to replicate a “RU” application.
- **Cement:** CSA Type GU Portland Cement
- **Mix Proportions:** Refer to Table 14 for RCA EV Mix Design.
- **Target Strength (f'c) and w/c ratio:** 25MPa (w/c = 0.65), 35MPa (w/c = 0.45), and 45MPa (w/c = 0.40)

*Table 14 - Group 7C: RCA EV Method*

Group Name	Mix #	Mix Name	Design f'c (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
7C (RCA EV Method)	59	(59): RCA EV: 27-SUP-NA	35	354	0	0	682	0	0	1165	160	0	0
	60	(60): RCA EV: 40-CL-25	25	261	0	0	712	0	0	1186	169	0	0
	61	(61): RCA EV: 46-CL-35	35	321	0	0	686	0	0	1223	145	0	0
	62	(62): RCA EV: 52-CL-45	45	335	0	0	707	0	0	1223	133	0	0

### 3.2.7.4 Group 7D: Fine RCA DR & EV Method Mix Design

The experimental program for the use of FRCA was completed by Macedo [11] which employed the direct replacement method and the EV method. Two FRCA families were produced: FRCA from natural (FRCA-NS) and manufactured (FRCA-MS) sand using two different manufacturing methods (i.e. crusher's fine - CF and fully ground - FG). The PSD for the final FRCA from both manufacturing methods ranged from 150 µm to 5 mm. Since 2 types of FRCA were produced using 2 different crushing methods, a total of 4 mixes were prepared using each of the DR and EV mix design methods. As expected, the DRM resulted in a high cement content and the EV method resulted in an average cement content. Below is a brief overview on the materials used within this mix:

- **Fine Aggregates:** Natural sand (NS) and Manufactured Sand (MS)
- **Coarse Aggregates:** Crushed limestone (Natural Aggregate) – No RCA.
- **Cement:** CSA Type GU Portland Cement
- **Mix Proportions:** Refer to Table 15 for Fine RCA DR & EV Mix Design.
- **Target Strength ( $f'c$ ) and w/c ratio:** 35MPa (w/c = 0.35)

*Table 15 - Group 7D: Fine RCA - DR & EV Methods*

Group Name	Mix #	Mix Name	Design $f'c$ (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
<b>7D</b> (Fine RCA - DR & EV Methods)	63	(63): RCA: DRM-NS CF	35	497	0	0	0	1032	524	0	174	0	0
	64	(64): RCA: DRM-NS FG	35	497	0	0	0	1032	546	0	174	0	0
	65	(65): RCA: DRM-MS CF	35	497	0	0	0	1032	533	0	174	0	0
	66	(66): RCA: DRM-MS FG	35	497	0	0	0	1032	551	0	174	0	0
	67	(67): RCA: EV-NS CF	35	373	0	0	0	1005	714	0	131	0	1.2
	68	(68): RCA: EV-NS FG	35	373	0	0	0	1014	740	0	131	0	1.2
	69	(69): RCA: EV-MS CF	35	372	0	0	0	1004	732	0	130	0	1.2
	70	(70): RCA: EV-MS FG	35	373	0	0	0	1006	752	0	131	0	1.2

### 3.2.8 Group 8: PPM Mix Proportioned RCA Concrete Materials and Methods

A novel approach using a combination of the FRCA EV method and a continuous PPM (Alfred model – standard PPM) was developed and assessed by Macedo [11]. The q-factor selected for the continuous PPM was  $q=0.28$  to ensure a suitable fresh state behavior when being combined with FRCA. Inert fillers were also introduced into the mix to further improve the fresh state behavior and reduce the cement content. The combination of FRCA, PPM, and the use of fillers yielded final PC contents ranging from 333 to 299 kg/m<sup>3</sup> (using a minimum of chemical admixtures). Below is a brief overview on the materials used within this mix:

- **Fine Aggregates:** Natural sand (NS) and Manufactured Sand (MS)
- **Coarse Aggregates:** Crushed limestone (Natural Aggregate) – No RCA.
- **Cement:** CSA Type GU Portland Cement
- **Mix Proportions:** Refer to Table 16 for PPM mix proportioned RCA concrete
- **Filler:** Limestone filler with a PSD smaller than the PSD of PC (Performance Filler)
- **Target Strength ( $f'c$ ) and w/c ratio:** 35MPa (w/c = 0.35)
- **Admixture:** Combination of polycarboxylate-based high range and mid-range water reducers

*Table 16 - Group 8: Combined PPM & Fine RCA EV Method Mix Design*

Group Name	Mix #	Mix Name	Design f'c (MPa)	Cement (Kg/m <sup>3</sup> )	Total Filler Content (Kg/m <sup>3</sup> )	SCM (Kg/m <sup>3</sup> )	FA (Kg/m <sup>3</sup> )	CA (Kg/m <sup>3</sup> )	FRCA (Kg/m <sup>3</sup> )	CRCA (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	SP Admixture (Kg/m <sup>3</sup> )	WR Admixture (Kg/m <sup>3</sup> )
8 (Combined PPM & RCA)	71	(71): RCA & PPM: NS CF	35	308	108	0	0	806	879	0	108	0	1
	72	(72): RCA & PPM: NS FG	35	333	83	0	0	797	907	0	117	0	1
	73	(73): RCA & PPM: MS CF	35	299	118	0	0	809	898	0	105	0	1.2
	74	(74): RCA & PPM: MS FG	35	332	84	0	0	798	915	0	116	0	1.2

### 3.3 RESULTS & ANALYSIS

The global ready-mix concrete market is growing rapidly and becoming more and more competitive. The demand for ready-to-mix concrete in the construction industry has surged significantly due to growing infrastructural development activities worldwide. Many of the large and reputable concrete producers are actively working on developing green concrete mixtures and beginning to sell these mixtures in the market. The price evaluation of these concrete mixtures in comparison to conventional concrete mixes is a very sensitive subject and is not defined within the literature. This topic is very difficult to define as it's largely affected by competition, trade secrets, supply, demand, market conditions, and material availability. The goal of this section is present the results of a comprehensive market research study on the total cost; review of global warming potential; and binder/carbon intensities of each of the sustainable concrete mix designs presented in section 5.4. In order to complete the comparative analysis, the first step was to establish a baseline cost/GWP for conventional concrete (CC) mixtures and "industry green concrete" which is CC with SCM replacement. The baseline results are presented in section 3.5.2 and are used in subsequent sections (3.3.5 to 3.3.8) for comparison purposes. To ensure the basis of these results is understood, there are various considerations/assumptions that were made which are presented in section 5.5.1.

#### 3.3.1 Basis of Results

Due to the subjective nature of the results in this study, the below items should be noted to ensure that the basis of these results is well understood:

- 1) The total costs presented in section 5.5.2 and 5.5.3 are based on the general pricing of core constituents of the concrete mixtures in the Ottawa, Ontario region and generally include for material procurement and production but do not account for any unique changes in market conditions, competition, supply and demand, overhead, profit, etc. The aforementioned factors impact the overall cost of these mixtures.
- 2) Geography and material availability play a major role in pricing of concrete mixtures and should be reviewed on an individual basis. Refer to section 3.5.4 for a more detailed explanation on the region's impacts on cost & GWP.
- 3) Concrete mixture prices are generally a variable of the compressive strength and therefore all 74 mixtures presented in section 5.4 were split into three categories: 1) low strength:  $f'c = 25\text{MPa}$  to  $34\text{MPa}$ ; 2) normal strength:  $f'c = 35\text{MPa}$  to  $44\text{MPa}$ ; 3) high strength:  $f'c \geq 45\text{MPa}$ . The reason for the split is to ensure that the costing, GWP, and  $bi/Ci$  factor results are all fairly evaluated against their corresponding baseline mix.

- 4) The results in sections 5.5.3 (cost) and 5.5.4 (GWP) exclude transportation and delivery of concrete from plant to the project site as this factor is dependent on a case by case basis. The overall cost of these mixtures should be adjusted to include for travel and delivery.
- 5) Costing & GWP are subjective depending on the source of data and therefore the focus of the results in this section should be on the relative difference to other mixtures (whether baselines or other sustainable mixes) and not the exact values as these may be interpreted differently in different regions and markets.
- 6) The following mixtures have been omitted from the results section for the reasons listed below:
  - Mixes 28, 40, and 41: all yielded f'c below 25MPa
  - Mixes 7 & 8: although using a PPM approach, yielded a higher cement content than CC
  - Mixes 43, 49, and 55: control mixes for RCA that did not use any LCC mix design methods
  - Mixes 63 to 66: Used the RCA DRM approach which yielded unfavorable results as expected

### 3.3.2 Industry Conventional & Green Concrete Baseline

A total of six concrete mixtures were selected to form as an “industry baseline” for conventional concrete and “green concrete” which are from groups 1 and 2 as per sections 3.4.1 and 3.4.2. The baseline cost, GWP, and binder/carbon intensities are tabulated in Table 17. The costs for these baseline mixtures were obtained through market research from multiple reputable concrete suppliers within the Ottawa area and the average was taken for comparative purposes. The GWP was gathered from the environmental product declaration manuals provided by the same suppliers to ensure a consistent baseline is provided. One of the reliable EPD’s used is by the CRMCA (Canadian Ready Mixed Concrete Association) [54]. The binder and carbon intensities were calculated as per the equations reviewed in section 3.2.4. These baselines results will be used for comparative purposes in all of the subsequent results sections.

*Table 17 - Baseline Results for Industry Conventional Concrete and Green Concrete*

Group Name	Mix #	Mix Name	Design f'c (MPa)	Cost (\$/m <sup>3</sup> )	GWP (Kg CO <sub>2</sub> / m <sup>3</sup> )	Binder Intensity (Kg/m <sup>3</sup> )/(MPa)	Carbon Intensity (Kg/m <sup>3</sup> )/(MPa)	I-SEE (MPa/GWP)*100
1 (ACI)	1	(1): ACI: 314-25	25	\$ 172	317	12.56	12.69	7.88
	2	(2): ACI: 370-35	35	\$ 183	368	10.57	10.50	9.52
	3	(3): ACI: 424-45	45	\$ 194	416	9.42	9.25	10.81
2 (SCM's)	4	(4): ACI-SCM-60-40-25	25	\$ 168	207	12.56	8.28	12.07
	5	(5): ACI-SCM-60-40-35	35	\$ 178	238	10.57	6.81	14.69
	6	(6): ACI-SCM-60-40-45	45	\$ 189	268	9.42	5.95	16.81

### 3.3.3 Constituent Breakdown

Market research via reputable concrete suppliers was completed to gather costing data for the different concrete constituents. The average of the unit cost for each of the constituents is tabulated in table 18 and shows that cement is the largest cost center after chemical admixtures which are typically used at a small quantity in concrete mix designs. When gathering cost data from concrete suppliers, several factors can introduce variability, including:

- 1) **Geographic Location** of each of these suppliers (Refer to section 3.5.4 for more detailed information)
- 2) **Type, Quality, and Source of raw materials** which include but are not limited to location of extraction, supply availability, demand for the same product by others, and transportation from extracted source to concrete plant.
- 3) **Supplier’s capacity, production scale, and infrastructure.** Supplier’s with larger infrastructure and more owned equipment are typically able to reduce their overall cost compared to others that have to outsource different tasks such as material storage, aggregate crushing, aggregates size distribution, preparation of chemical admixtures, etc.
- 4) **Pricing strategies, Operational Efficiencies, Order sizes based on capacity, and use of concrete technologies (custom or specialized mix designs)**

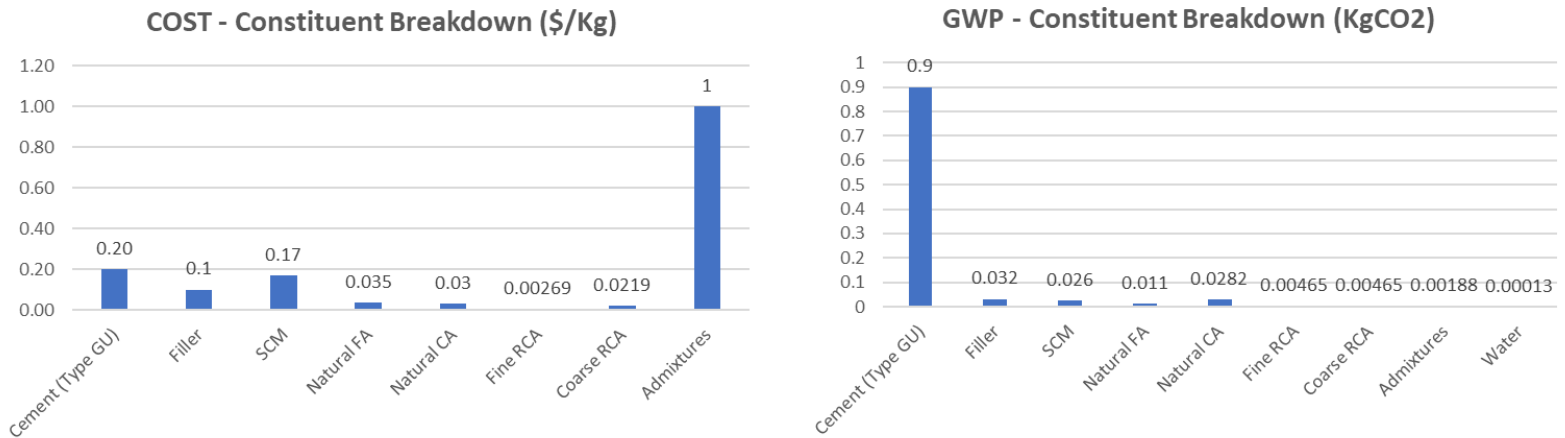
The unit cost of aggregates (whether natural or RCA) is considered negligible to the cost of cement, fillers, and SCM’s; therefore the main focus in concrete mix designs is to ensure we can either: 1) reduce the amount of binder as much as possible while maintaining the required properties (fresh, hardened, and long term durability), 2) Replacement of cement with fillers and SCM’s to further reduce the overall cost.

Table 18 also shows the average GWP constituent breakdown gathered via the two previously cited and discussed LCA tools developed by Global Cement and Concrete Association (GCCA) and the Slag Cement Association (SCA). The results further highlight how cement use/production has significantly higher CO<sub>2</sub> emissions compared to all the other ingredients and this further reinforces that controlling the cement content within concrete mixtures is the most effective method to ensure an eco-efficient concrete mix design.

*Table 18 – Unit Cost & Global Warming Potential (GWP) Constituent Breakdown*

Constituent	Cement (Type GU)	Filler	SCM	Natural FA	Natural CA	Fine RCA	Coarse RCA	Admixtures	Water	Concrete Production
Unit Cost	\$0.2/Kg	\$0.1/Kg	\$0.17/Kg	\$0.035/Kg	\$0.030/Kg	0.0269/Kg	0.0219/Kg	\$1/Kg	\$4.26/m3	\$50/m3
GWP (KgCO2)	0.9	0.032	0.026	0.011	0.0282	0.00465	0.00465	0.00188	0.00013	4.65

The tabulated results from table 18 have been plotted on a bar chart and presented in figure 19 to show a visual comparison between the cost/GWP of cement compared to all other constituents. The variation in the output between GCCA & SCA LCA tools was less than 5% which aided in the verification that the baseline constituents GWP values being used have a high level of certainty.



*Figure 19 – Left: Cost Constituent Breakdown Comparison; Right: GWP Constituent Breakdown*

### 3.3.4 Region Impact on Cost & GWP

The region or location where concrete is produced and used can significantly impact both its cost and Global Warming Potential (GWP). These impacts arise from variations in factors such as the availability of raw materials, energy sources, transportation logistics, climate conditions, and recycling infrastructure. Below is a detailed explanation of how these factors influence the cost and GWP of concrete:

#### 1) Availability of Raw Materials

- Cost Impact:** The availability of key raw materials like aggregates, sand, water, and cementitious materials (e.g., Portland cement, fly ash, slag) varies by region. In regions where these materials are abundant and locally sourced, the cost of concrete tends to be lower due to reduced transportation expenses and high supply. Conversely, in areas where raw materials are scarce or need to be imported, costs increase.
- GWP Impact:** The environmental impact of sourcing raw materials also varies by location. Regions with abundant local materials reduce the need for long-distance transportation, which in turn reduces associated carbon emissions. In contrast, importing materials over long distances increases the GWP of concrete due to higher fuel consumption and transportation emissions.

## 2) Energy Sources

- **Cost Impact:** The type and cost of energy used in concrete production are heavily influenced by regional energy sources. In areas where electricity is generated from renewable sources or where energy is inexpensive, the cost of producing concrete can be lower. However, regions relying on expensive or non-renewable energy sources may face higher production costs.
- **GWP Impact:** The carbon footprint of concrete is significantly affected by the energy mix in the region. Regions that rely on fossil fuels for energy, such as coal or natural gas, typically have a higher GWP for concrete production. In contrast, regions that use cleaner energy sources, such as hydropower, wind, or solar, have lower GWP, making the concrete produced there more environmentally friendly.

## 3) Transportation and Logistics

- **Cost Impact:** Transportation is a major cost factor in the concrete industry due to the heavy and bulky nature of concrete and its raw materials. The proximity of production facilities to construction sites and raw material sources directly influences transportation costs. In urban or industrial regions with well-developed infrastructure, transportation costs may be lower. In contrast, remote or underdeveloped regions may face higher costs due to longer transportation distances and less efficient logistics.
- **GWP Impact:** Longer transportation distances increase fuel consumption and carbon emissions, thereby increasing the GWP of concrete. Regions with efficient transportation networks and shorter supply chains have a lower GWP associated with concrete transportation.

## 4) Climate Conditions

- **Cost Impact:** Regional climate conditions can influence the cost of concrete in several ways. For example, in colder climates, the production and curing of concrete may require additional energy and time, increasing costs. In hot or arid regions, the need for water and cooling during production and curing can also raise costs. Moreover, extreme weather conditions can affect construction schedules, leading to potential cost overruns.
- **GWP Impact:** The climate also affects the carbon footprint of concrete production. In regions with cold climates, the additional energy required for heating during production and curing can lead to higher GWP. Conversely, in regions with milder climates, less energy may be needed, resulting in a lower GWP.

## 5) Local Regulations and Standards

- **Cost Impact:** Local building codes, environmental regulations, and sustainability standards can vary significantly by region. In regions with stringent environmental regulations, producers may need to invest in cleaner technologies or more sustainable practices, which can increase production costs. On the other hand, regions with fewer regulations may have lower production costs but potentially higher long-term environmental and health costs.
- **GWP Impact:** Regulations can directly influence the GWP of concrete by setting limits on emissions or requiring the use of certain sustainable materials and practices. For example, regions with regulations promoting the use of supplementary cementitious materials (e.g., fly ash, slag) in concrete can reduce the GWP of the material. In contrast, regions with less stringent regulations may see higher GWP due to less emphasis on reducing carbon emissions.

## 6) Recycling and Waste Management Infrastructure

- **Cost Impact:** Regions with well-developed recycling and waste management infrastructure can reduce the cost of concrete by incorporating recycled aggregates and other materials into the mix. This can also reduce disposal costs for construction waste. Conversely, in regions where such infrastructure is lacking, the cost of using virgin materials may be higher, and there may be fewer opportunities to reduce costs through recycling.
- **GWP Impact:** The availability of recycling infrastructure directly affects the GWP of concrete. Regions that effectively recycle construction waste and use recycled aggregates can significantly lower the GWP of concrete. This is because the production of recycled materials generally has a lower carbon footprint compared to the extraction and processing of virgin materials.

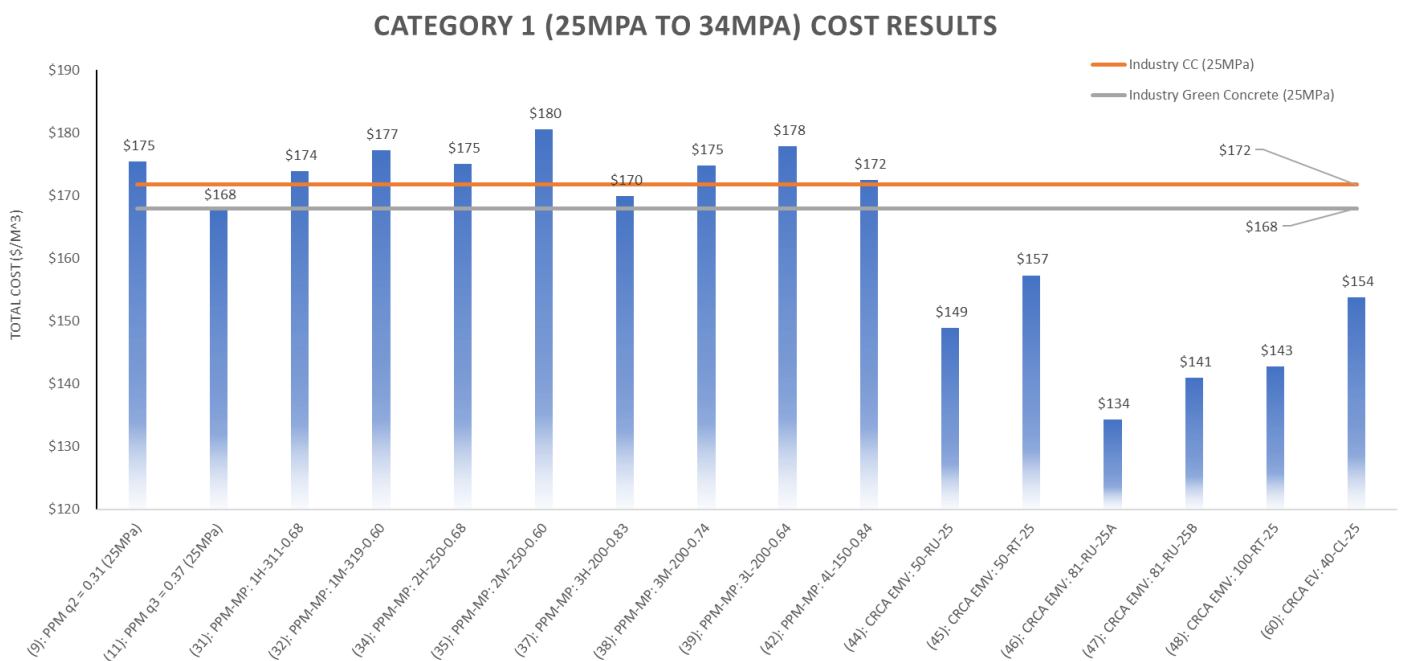
The region or location has a profound impact on both the cost and GWP of concrete. Factors such as the availability of raw materials, energy sources, transportation logistics, climate conditions, local regulations, and recycling infrastructure all play critical roles in determining these impacts. As the construction industry continues to focus on sustainability, understanding and addressing these regional differences will be essential in reducing the environmental footprint of concrete and optimizing costs.

### 3.3.5 Cost Evaluation

Costs for each of the sustainable concrete mix designs were evaluated by completing market research in collaboration with reputable concrete suppliers. Market research yielded different costs per quantities of materials which were translated into overall mix design costs per cubic meter by taking into consideration the different materials and different quantities for each of the constituents the mixes. The costs presented in this section consider the material extraction requirements and different production requirements. It is important to note that although each supplier provided different sets of data, the average was used in all cases and the goal of the evaluation is to compare the costs between the different mixes especially to the baseline mixes as the costing may be subjective based on the factors previously mentioned in section 5.5.1.

#### 3.3.5.1 Category 1 (25MPa to 34MPa) Cost Evaluation

Figure 20 represents the cost evaluation for category 1 mixes (total of 16) where they are compared to the baselines mixtures (industry CC & industry green concrete). The results show that in the low strength category (25MPa to 34MPa), the use of the RCA EMV and EV mix design methods (mixes 44 to 48 & 60) yielded the most cost-effective results (up to 20% reduction in costs) compared to both industry CC & GC. The use of re-used RCA's also proved to be more cost effective than returned RCA. PPM mix designs in the low strength category yielded generally the same costs as industry CC & GC.



*Figure 20 - Cost Results for Category 1 Mixes (25MPa to 34MPa)*

### 3.3.5.2 Category 2 (35MPa to 44MPa) Cost Evaluation

Figure 21 represents the cost evaluation for the normal strength category where there is a total of 31 mixes compared to the baselines industry mixtures. This category represents the mixes generally used within the industry for most structural applications and therefore is considered of highest importance in this review. PPM mix designs performed as expected where the OPPM mix design (mix #18) yielded the lowest cost compared to all other PPM mix designs and resulted in a 11% reduction in cost compared to industry GC. The use of PPM's in combination with SCM's (Mix #22 & #26) yielded a similar result to OPPM which prove that the use of PPM's as part of the industry GC will create a more cost effective mix while also maintaining an acceptable fresh state behavior. CRCA mix designs 50, 52 to 54, and 56 have proven to be cost effective showing a reduction ranging between 11% to 21% whereas FRCA mixes (67 to 74) yielded generally similar cost results to industry GC. The difference in costs between CRCA and FRCA can be attributed to the superior fresh state performance in the FRCA mix designs which also uses the EV method compared to the EMV method used for the CRCA mixes. From a pure cost perspective, the use of CRCA's yield the most cost efficient mixes but it is important that this study is further complemented with the lifecycle performance of this mix to ensure a complete lifecycle cost analysis is used for decision making.

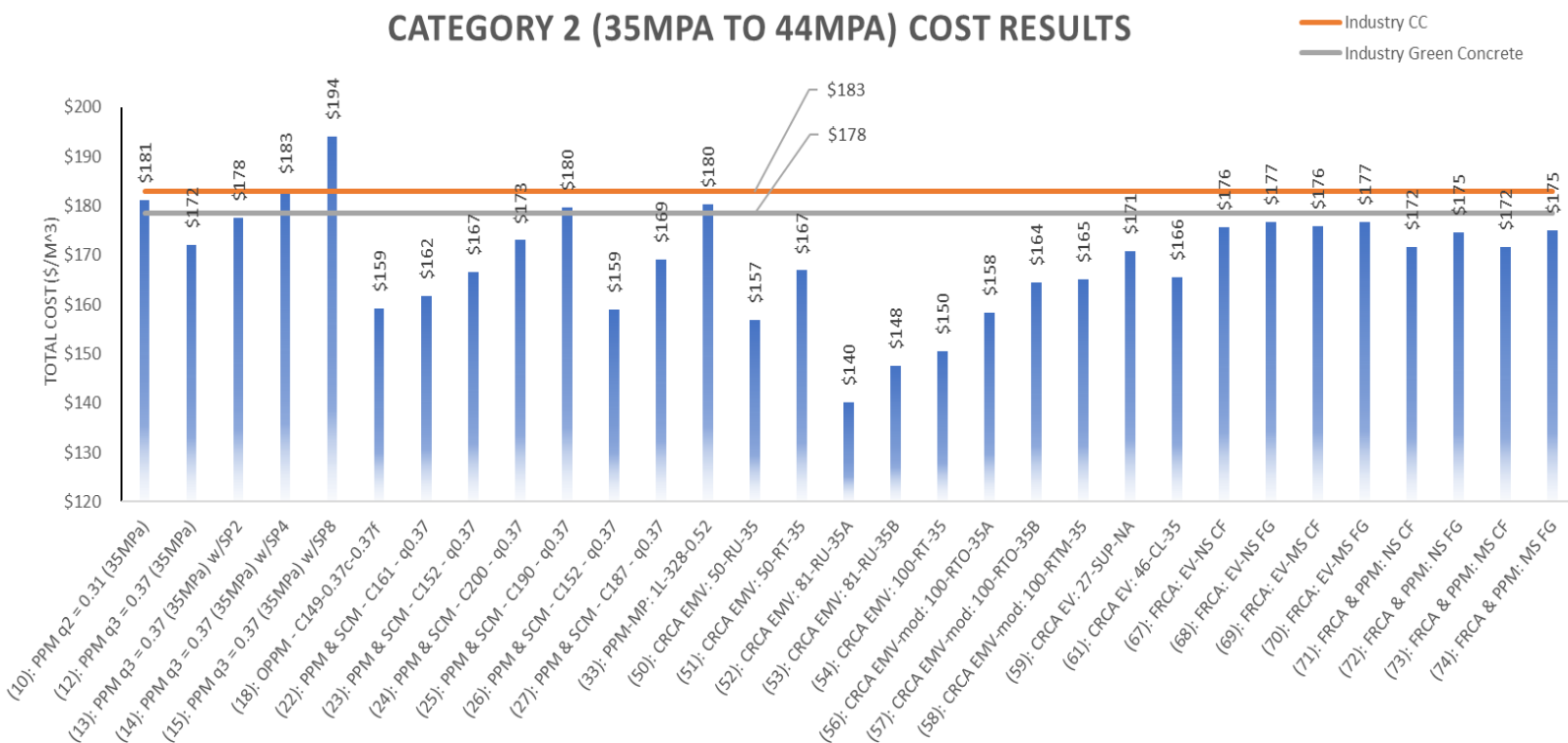
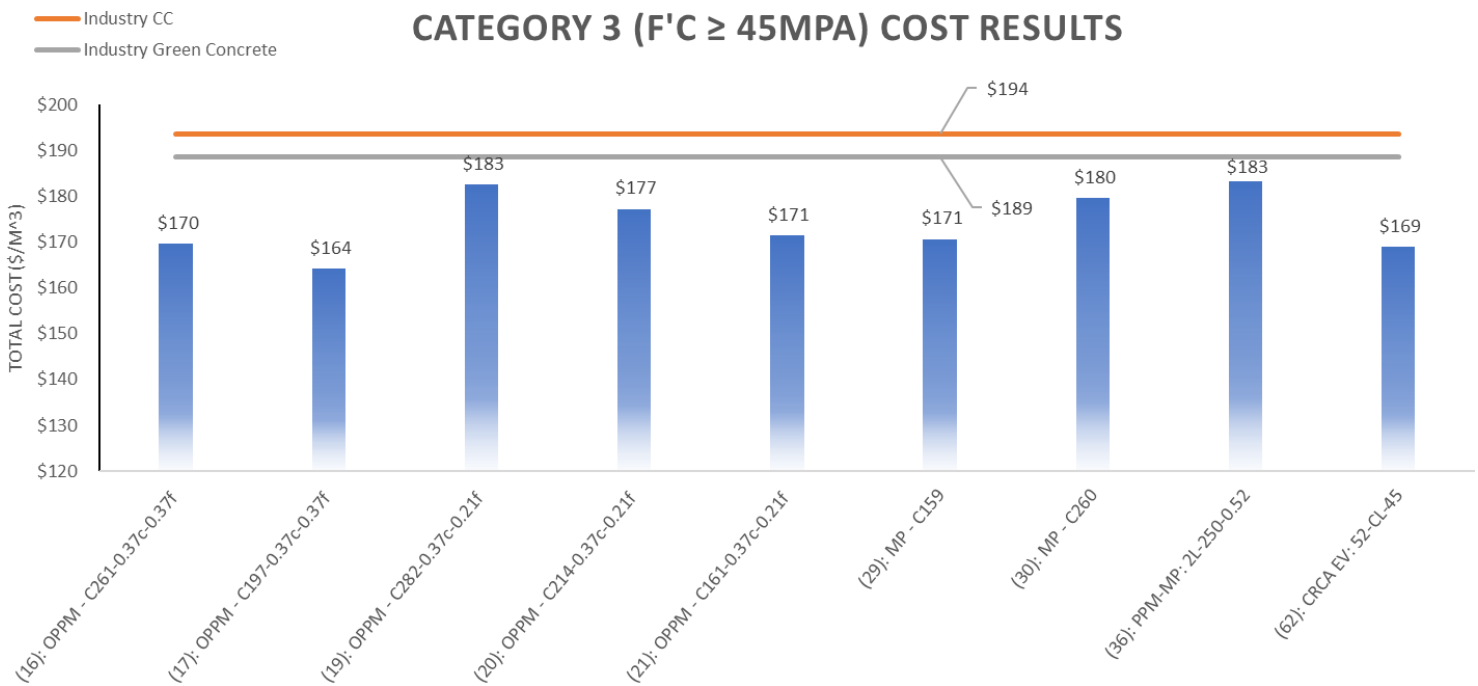


Figure 21 - Cost Results for Category 2 Mixes (35MPa to 44MPa)

### 3.3.5.3 Category 3 (F'C ≥ 45MPa) Cost Evaluation

Figure 22 represents the cost evaluation for the high strength concrete category where there is a total of 9 mixes compared to industry CC and GC. It is very evident that in the high strength category, all sustainable mix designs result in a lower cost compared to industry CC & GC. OPPM all show a cost reduction within the range of 3% to 13% and specifically for mix #19 the fresh state behavior is superior to the fresh state of industry CC & GC. Mixes 29 & 30 using the MP mix design methodology not only yield a 9% and 5% cost reduction respectively but also yield a high flow slump of 615mm which is categorized as self-consolidating concrete (SCC) which is used in tightly reinforced areas where effective vibration mechanisms are not possible. SCC mixtures are typically 1-1.5 times the cost of standard CC and therefore it is evident that in high flow applications, the use of MP mixtures will result in substantial savings in the order of 100% to 160% of the cost compared to typical SCC mixtures. Mix #62 using CRCA through the EV method also yielded very favorable results which represent a 10% reduction in cost and the same fresh state behavior as conventional concrete.



*Figure 22 - Cost Results for Category 3 Mixes (F'C ≥ 45MPa)*

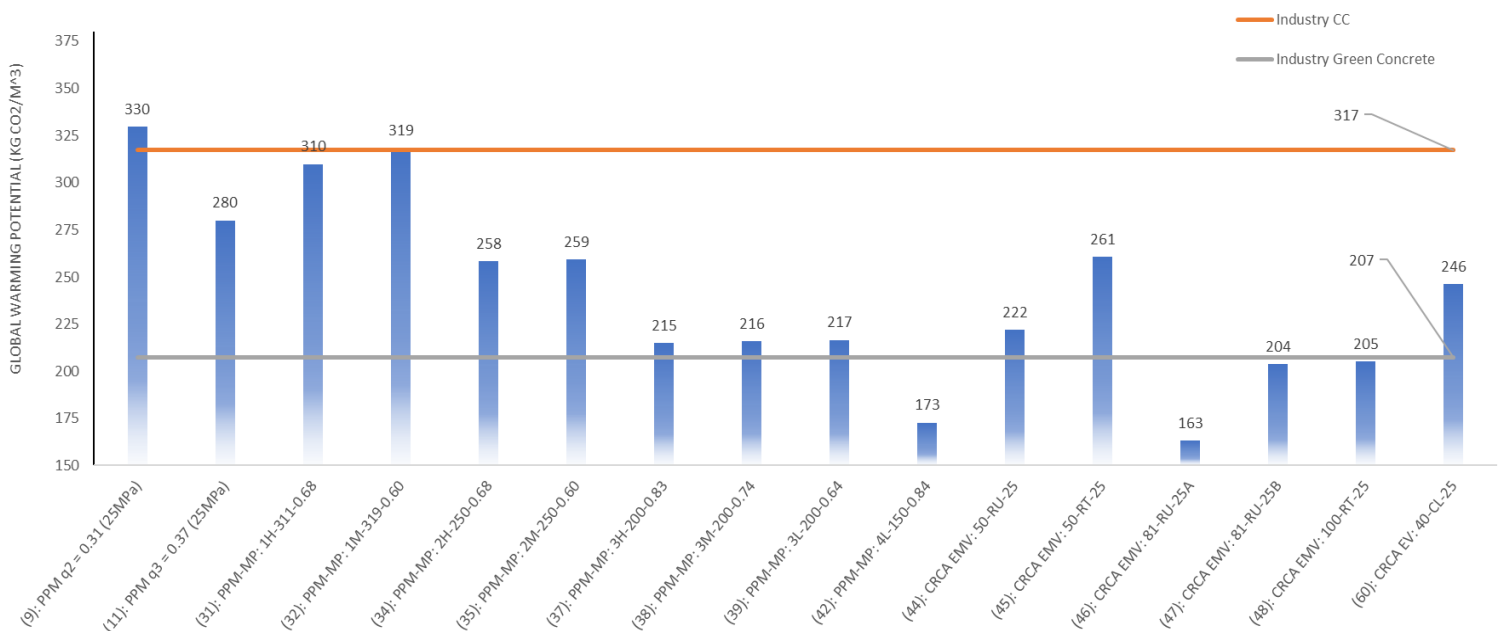
### 3.3.6 Global Warming Potential Evaluation

Global warming potential was evaluated through a variety of life cycle analysis (LCA) tools which were outlined in section 1.5.3 and average results are presented in this study. The system boundaries considered for this evaluation were from “cradle to gate” which only includes the product stages A1 to A3. A1 is the raw material extraction/processing and processing of secondary material input; A2 is transport of the material to the manufacturer; and A3 is the manufacturing process. This boundary does not include the construction process stage (i.e transport to site and installation) or any of the subsequent stages. Although there is no clear relationship between GWP and compressive strength, all the mix designs have been split into the same three categories for the sake for consistency in the results between the different sections.

#### 3.3.6.1 Category 1 (25MPa to 34MPa) GWP Evaluation

Figure 23 represents the global warming potential evaluation for the low strength category compared to industry CC & GC. As shown, all the mixes except for mix #9 have resulted in a lower GWP than conventional GWP but only 2 mixes have shown a reasonable reduction in GWP compared to industry GC which are mixes 42 and 46. Mix #42 using a combination of PPM and MP presented a 17% GWP reduction compared to industry GC and mix #46 using the CRCA EMV approach presented a 21% GWP reduction compared to industry GC.

**CATEGORY 1 (25MPa TO 34MPa) GWP RESULTS**



*Figure 23 - GWP Results for Category 1 Mixes (25MPa to 34MPa)*

### 3.3.6.2 Category 2 (35MPa to 44MPa) GWP Evaluation

Figure 24 represents the global warming potential evaluation for the normal strength category compared to industry CC & GC. The use of SCM as PC replacement (branded as industry GC) already reduces the GWP by 35% which is already a substantial reduction and therefore there are only 8 other mixtures that were able to further reduce GWP. All other mixes yielded GWP's between the two baseline data points (industry CC & GC). The OPPM mix #18 yielded a GWP of 180 Kg CO<sub>2</sub>/m<sup>3</sup> which is 51% lower than industry CC and 24% lower than industry GC representing a major improvement in the goal to reduce GWP. The combinations of PPM & SCM mixtures #22 to #26 yielded very favorable results which prove that combining both approaches is a very positive impact to overall GWP in the range of 10% up to 28%. The use of CRCA via the EMV and EV method yielded favorable results when compared to CC but only one mix (#52) yielded a significant GWP reduction of 21% compared to industry GC. The use of FRCA yielded the same GWP as industry CC, but the use of FRCA in combination with PPM's improved the GWP in the range of 9% to 17%. The results shown in figure 24 confirm that the PPM and SCM approach either individually or in combination are the best approach in the mitigation of global warming and achieving carbon reduction goals.

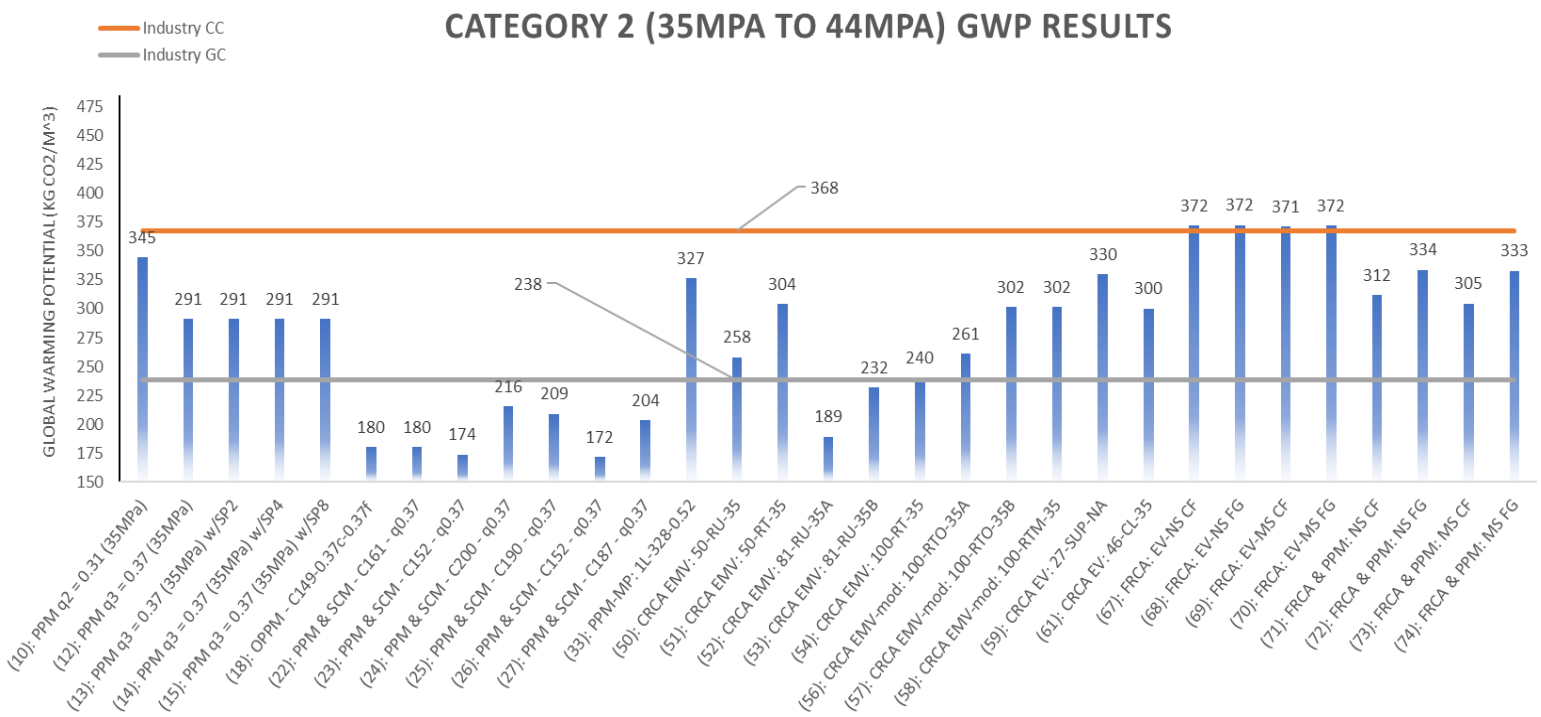
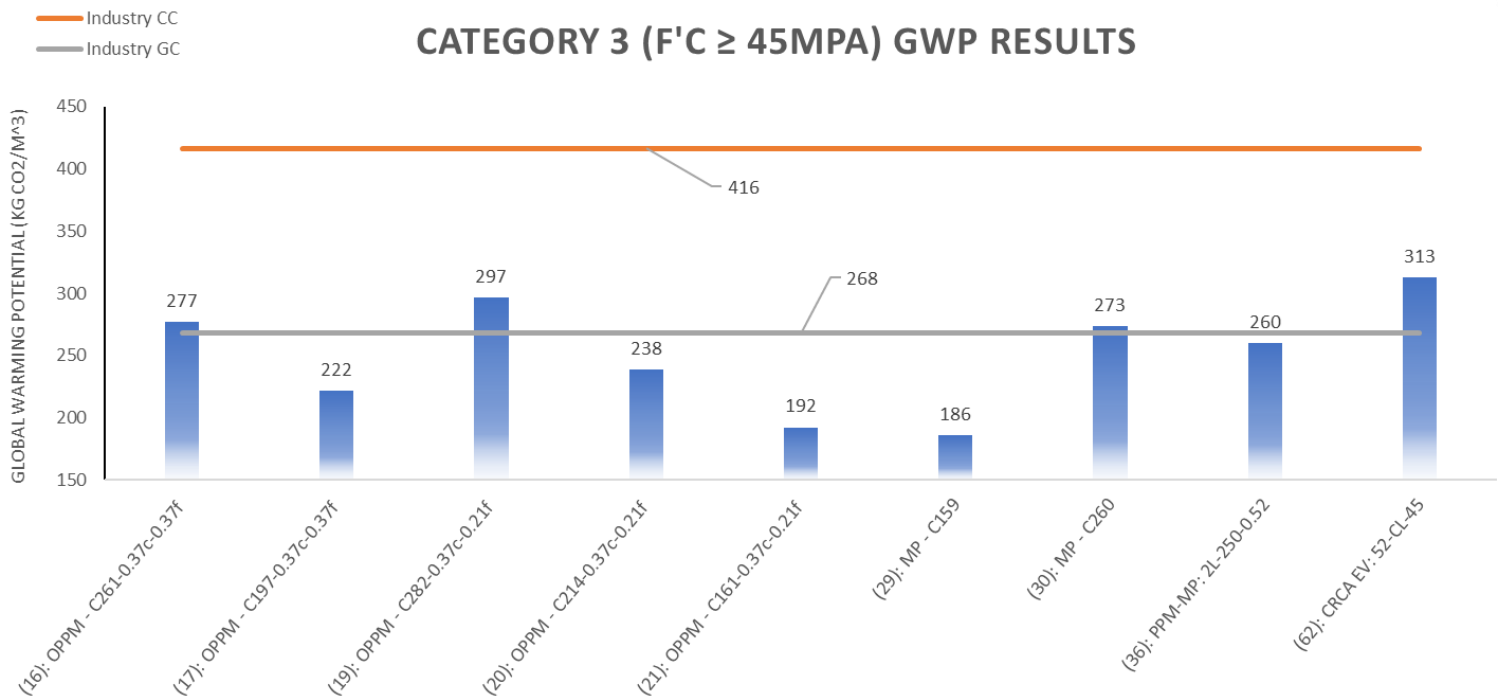


Figure 24 - GWP Results for Category 2 Mixes (35MPa to 44MPa)

### 3.3.6.3 Category 3 ( $F'C \geq 45\text{MPa}$ ) GWP Evaluation

Figure 25 represents the global warming potential evaluation for the high strength category compared to industry CC & GC. All of the mixtures within this category are either generally inline with the GWP of industry GC or have a lower GWP. For OPPM mixtures, the GWP is directly proportional to the cement content within the mixture which is evident from the results presented. Mixtures #17 & #21 yielded a GWP reduction of 17% and 28% respectively compared to industry GC which only used SCM as a replacement for PC. The use of mobility parameters yielded favorable GWP results especially for mix #29 which only has  $159 \text{ Kg/m}^3$  and therefore resulted in a 30% reduction in GWP compared to industry GC and 55% reduction in GWP compared to industry CC.



*Figure 25 – GWP Results for Category 3 Mixes ( $F'C \geq 45\text{MPa}$ )*

### 3.3.7 Binder & Carbon Intensity Evaluation

Binder and Carbon intensities were evaluated based on Damneli’s relationship outlined in section 5.2.5. The binder efficiency factor is a function of the quantity of binder to obtain a unit of strength and therefore the use of SCM’s as a replacement to PC although more eco-efficient, does not make the use of the binder more efficient and hence does not change the bi factor. The binder efficiency factor is valuable to understand how much binder is required to achieve a unit of strength. The carbon efficiency factor (Ci) is similar to Bi but is specific to the quantity of CO<sub>2</sub> emitted per unit of strength which translates to the GWP evaluated through the prediction models divided by the compressive strength. The Ci factor is the relationship between GWP and compressive strength. The results for Bi and Ci factors are presented in the same three categories.

#### 3.3.7.1 Category 1 (25MPa to 34MPa) Bi & Ci Evaluation

Figure 26 represents the binder and carbon intensity results for the low strength category compared to industry CC & GC. Generally the majority of the mixtures have a lower binder intensity than industry CC & GC since the use of the binder is more efficient with the use of the PPM, MP, and RCA mix design methodologies compared to the standard ACI mix design method. For carbon intensity, industry GC already represents a 35% reduction in carbon intensity and this is through the use of SCM’s only. The use of PPM’s in combination with MP’s show a further reduction in the range of 8% to 23%. CRCA’s using the EMV method also show a 21% reduction.

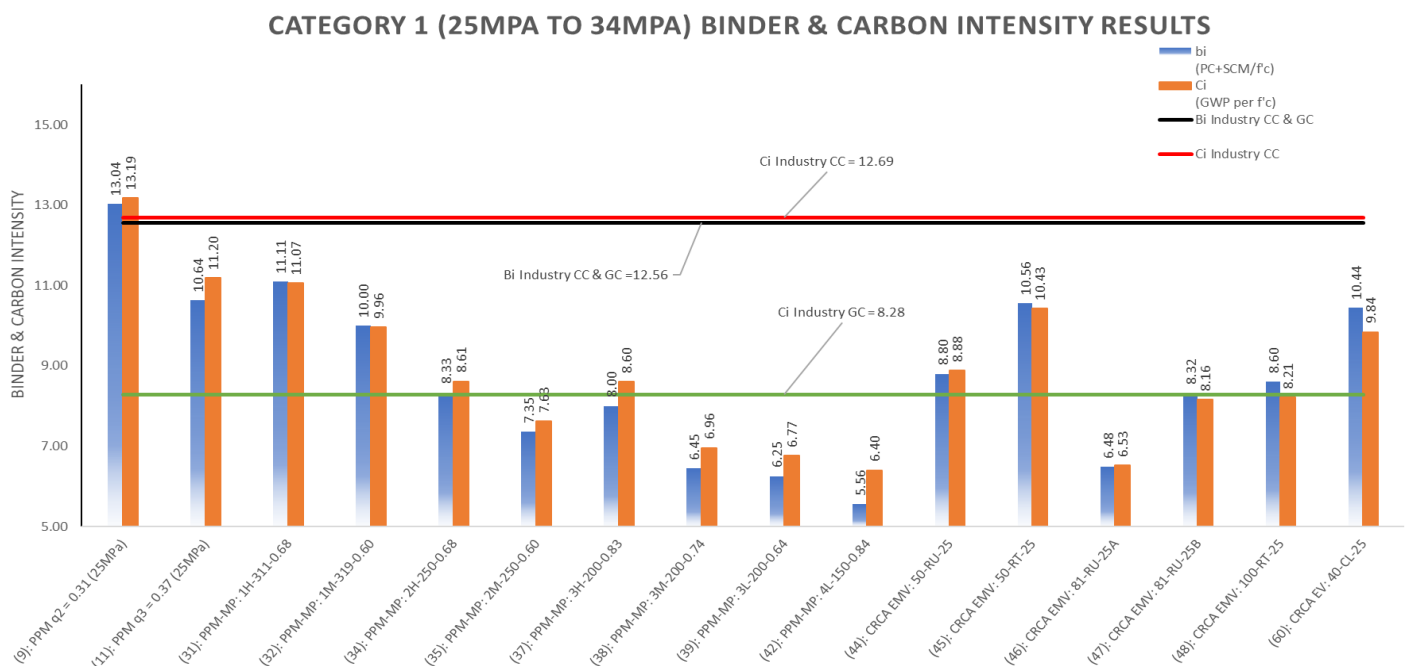


Figure 26 - Binder & Carbon Intensity Results for Category 1 Mixes (25MPa to 34MPa)

### 3.3.7.2 Category 2 (35MPa to 44MPa) Bi & Ci Evaluation

Figure 27 represents the binder and carbon intensity results for the normal strength category compared to industry CC & GC. Similar to the results from category 1, all mixtures have a lower binder intensity than industry CC and GC and this is due to the more efficient use of binders with the LCC mix design approaches. Under the PPM approach, mix #18 incorporates the most efficient use of binder compared to other mixtures and has a 67% reduction compared to industry CC & GC. Under the RCA approach, mix #52 which incorporates re-used CRCA through the EMV method has the most efficient binder usage compared to other mixtures and is also 48% lower than industry CC & GC. All mixtures in this category yielded a carbon intensity lower than or equal to industry CC but only 9 of 31 mixtures yielded a carbon intensity below industry GC. The OPPM approach has proven to be the most carbon efficient mixture with a Ci factor lower than industry CC by 60% and lower than industry GC by 38%. The combination of PPM's & SCM's (mixes 22 to 27) also yielded favorable carbon efficiency results in range of 10% to 27% lower than industry GC. RCA mixtures generally resulted in lower carbon intensities when compared to industry CC but only 1 mixture stood out to have a significant reduction when compared to GC which was mixture #52 – CRCA EMV using re-used material. The results in this section show that both PPM & RCA approaches are viable in mitigation of global warming potential and achieving carbon efficiency when compared to industry CC.

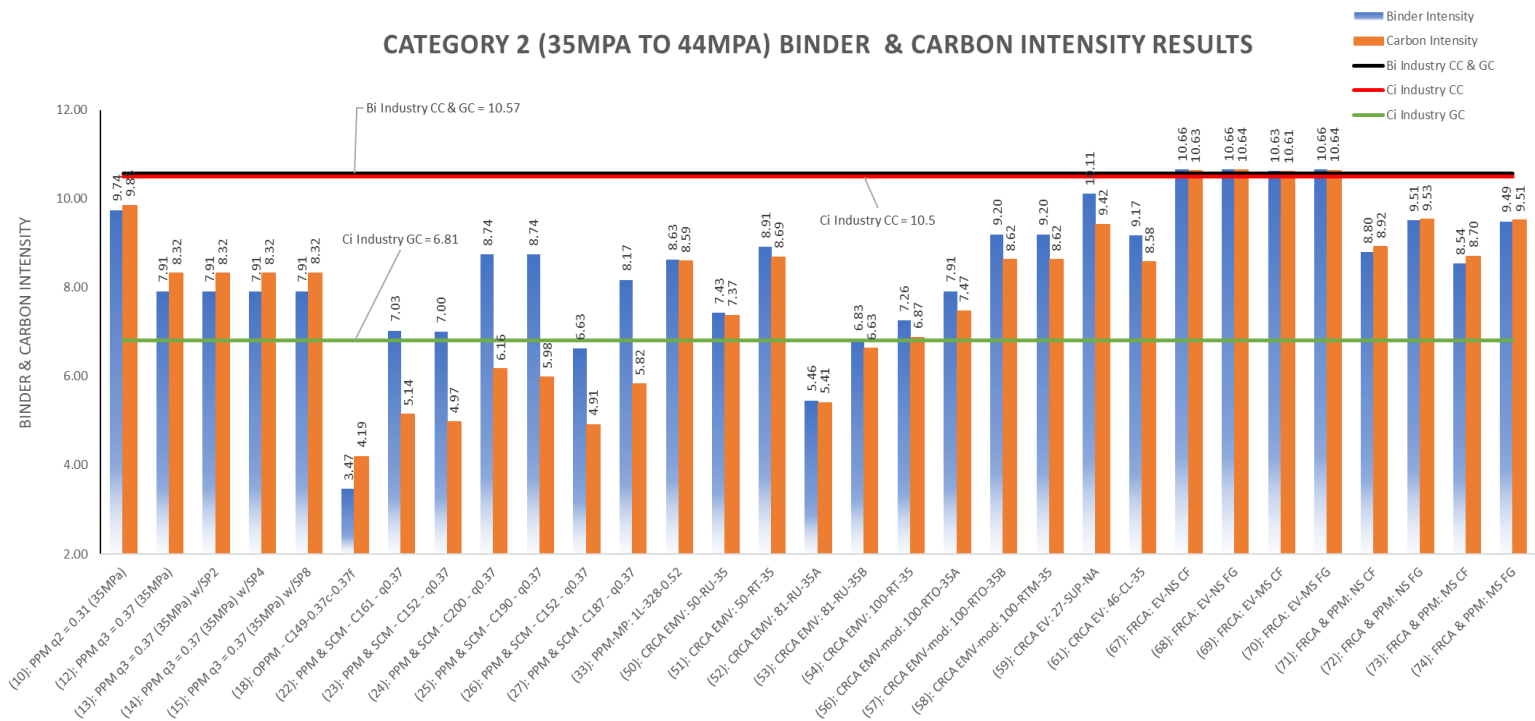


Figure 27 - Binder & Carbon Intensity Results for Category 2 Mixes (35MPa to 44MPa)

### 3.3.7.3 Category 3 ( $F'C \geq 45\text{MPa}$ ) Bi & Ci Evaluation

Figure 28 represents the binder and carbon intensity results for the high strength category compared to industry CC & GC. All mixtures within this category yield binder and carbon intensities lower than industry CC by minimum of 21% and up to 66%. When compared to industry GC, only 1 mixture (#62) exceeds industry GC whereas all other mixes within this category are also lower than industry GC which shows that the focus of binder and carbon efficiency should not be on the high strength category but more so on the normal strength concrete category. Carbon efficiency results show a direct co-relation between GWP and cement content for each of the mixtures since none of the mixtures within this category include for the use of SCM's. OPPM mixtures show a reduction between 27% to 35% compared to industry GC and this is mainly attributable to the ability to pack the mix and reduce the need for cementitious material to bond the system. The use of mobility parameters for high strength concrete applications has proven to provide superior eco-efficiency where mix #29 yielded a 30% reduction compared to industry GC and mix #30 yielded a 34% reduction compared to industry GC. Although mix #30 has approximately 100 Kg/m<sup>3</sup> more cement content, it yielded 25MPa more which resulted in a lower carbon intensity.

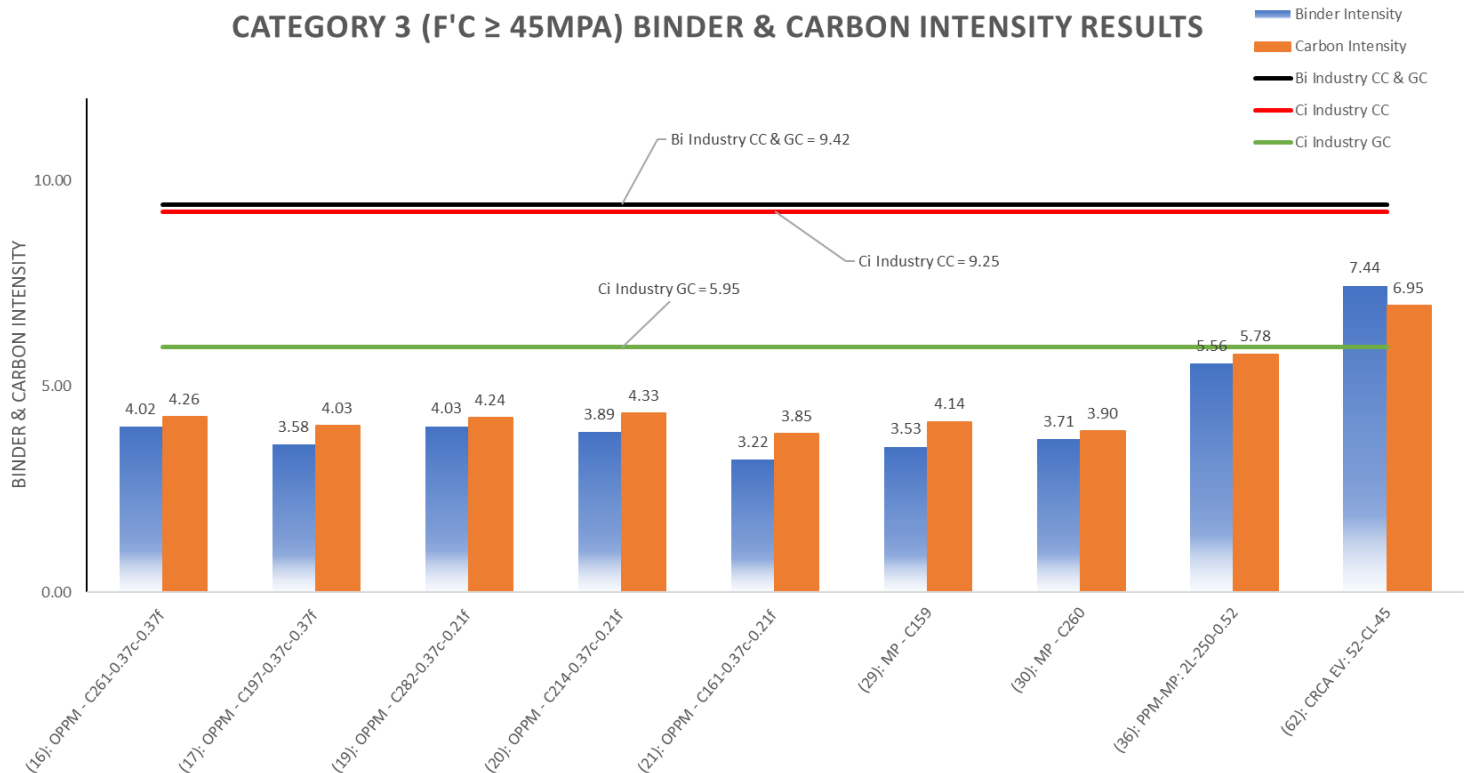


Figure 28 – Binder & Carbon Intensity Results for Category 3 Mixes ( $F'C \geq 45\text{MPa}$ )

### 3.3.8 Integrated Strength Eco-Efficiency (I-SEE) Coefficient

The integrated strength eco-efficiency co-efficient was evaluated based on the relationship outlined in section 5.2.5. The results were tabulated in figures 29, 30, and 31 for low, normal, and high strength categories respectively. The same trends as the carbon intensity are quantified but in the review of these figures, a high I-SEE value corresponds to a higher eco-efficiency whereas with carbon intensity, the lower value corresponds to a higher eco-efficiency. The significance of the I-SEE coefficient will become apparent in the next section.

For low strength mixtures (category 1), the combined approach of PPM & MP yielded the best strength eco-efficiency whereas for normal strength mixtures (category 2), the use of OPPM and combined PPM/SCM also yielded superior results compared to industry GC. For both low and normal strength concrete, the use of CRCA under the EMV method with 81% replacement yielded very similar I-SEE to the combined PPM/MP and combined PPM/SCM approach. For high strength mixtures, all except one exceeded the I-SEE for industry GC which shows that for high strength mixtures LCC mixes are almost always able to outperform industry CC & GC.

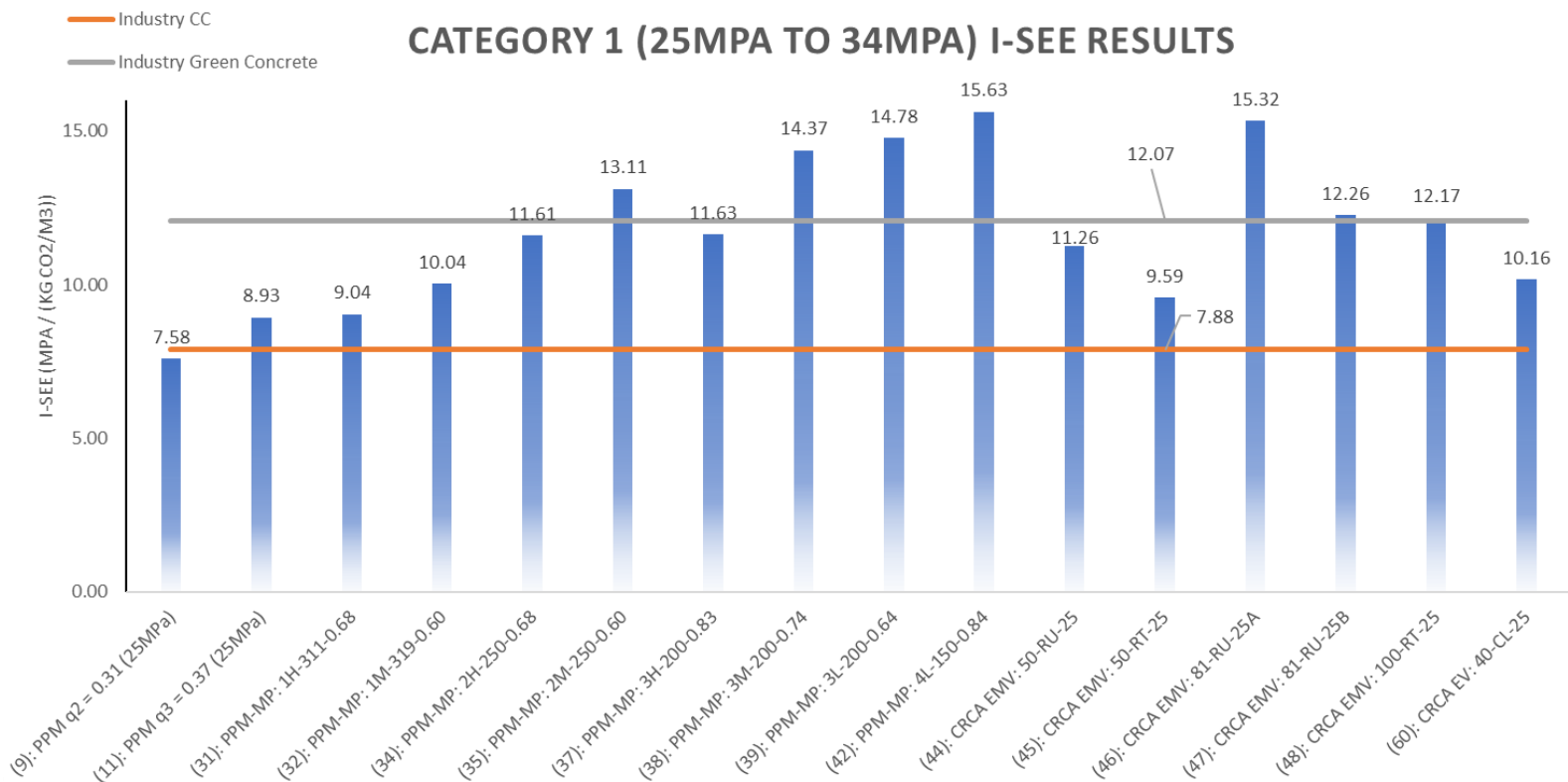


Figure 29 - Integrated Strength Eco-Efficiency (I-SEE) Results for Category 1 (25MPa to 34MPa)

### CATEGORY 2 (35MPa TO 44MPa) I-SEE RESULTS

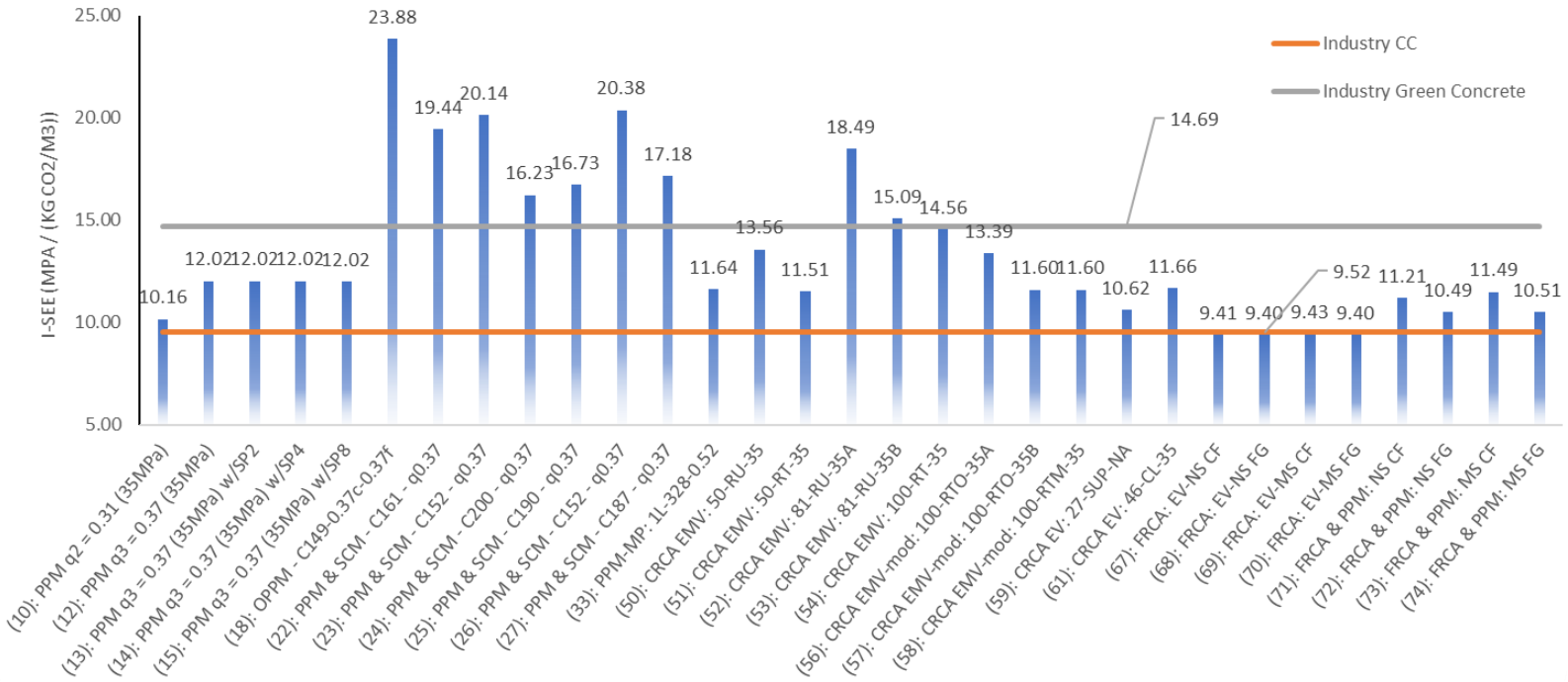


Figure 30 - Integrated Strength Eco-Efficiency (I-SEE) Results for Category 2 (35MPa to 44MPa)

### CATEGORY 3 (F'C ≥ 45MPa) I-SEE RESULTS

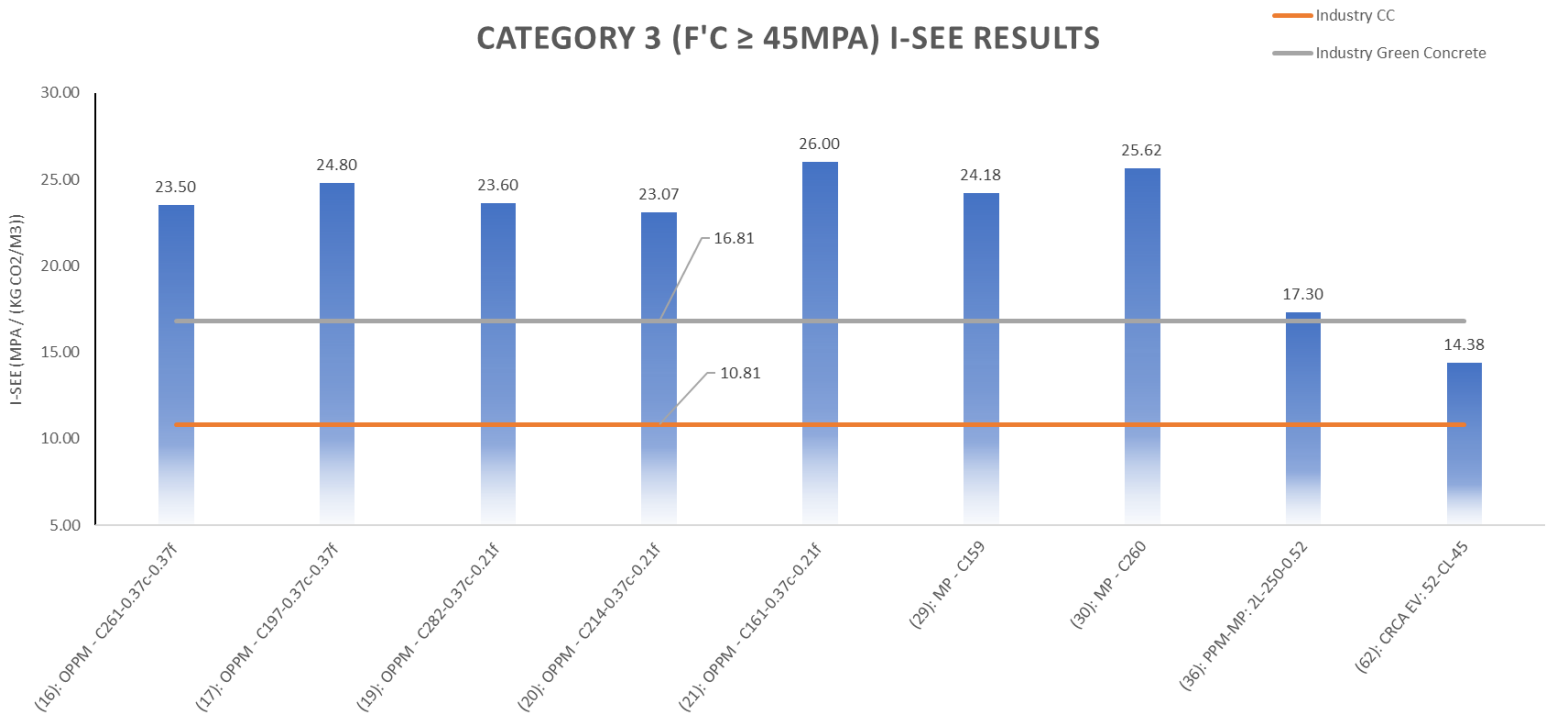


Figure 31 - Integrated Strength Eco-Efficiency (I-SEE) Results for Category 3 (F'C ≥ 45MPa)

### 3.4 NEW RELATIONSHIPS BETWEEN COST, STRENGTH, AND ECO-EFFICIENCY

Strength and eco-efficiency have been considered and studied in previous literature in various ways and this work evaluated the relationship between strength and eco-efficiency through the carbon intensity and I-SEE factors. The new parameter quantified as part of this study that is not very common within the literature is the cost of these LCC mixtures; consequently, new relationships are required to integrate cost with eco-efficiency and cost with strength and eco-efficiency. These new relationships will help provide designers and decision makers specify a quantifiable parameter that will control cost as a function of the desired eco-efficiency and cost as a function of concrete strength and eco-efficiency. The use of GWP, carbon intensity, and I-SEE do not consider the cost and therefore designers and decision makers may be specifying concrete mixtures that exceed their budget without full knowledge of this until the onset of the project. These new relationships will also aid in the selection of the different mixtures based on the application/importance of the structure being constructed.

#### 3.4.1 Carbon Cost Intensity (CCI) Factor

The first relationship developed as part of this work is between environmental impact (expressed as GWP in Kg CO<sub>2</sub>-eq/ m<sup>3</sup>) and cost (expressed in \$/m<sup>3</sup>), this factor has been named “Carbon Cost Intensity (CCI)”. The carbon cost intensity factor is represented in the following equation:

$$CCI = GWP \times Cost$$

The concept behind the CCI factor, while simple, is able to provide valuable input as a design parameter for all concrete mix designs as the quantity of CO<sub>2</sub> emissions in Kg/m<sup>3</sup> for every dollar spent. This factor should be used to compare mix designs within the same strength category to ensure a fair comparison. Designers and performance specification writers can specify the required compressive strength for a concrete with the CCI factor and this will provide concrete suppliers with sufficient information on the criteria for cost and eco-efficiency that they need to meet. A higher value of CCI corresponds to a lower carbon cost efficiency whereas a lower value of CCI corresponds to a higher carbon cost efficiency. The CCI factor was evaluated for all the LCC mixtures as part of this work and presented in figures 32, 33, and 34 for low, normal, and high strength categories respectively. For the low strength concrete category (figure 32), four mixtures yielded better CCI results than industry GC which was the combination of PPM and MP with the use of 150 Kg/m<sup>3</sup> of PC as well as use of CRCA via the EMV method. For normal strength concrete (figure 33), all OPPM, combined PPM/SCM mix designs, and three of the CRCA EMV mixtures yielded a more efficiency carbon cost intensity when compared to industry GC which proves that these mix designs are promising and should continue to be used in practice for cost and carbon

efficiency. For high strength concrete (figure 34), OPPM mixtures yielded varying results where 4 of 9 mixtures stood out and yielded a lower CCI factor than industry GC. The other 5 mixtures were on the border of the industry GC which shows positive impact compared to industry CC.

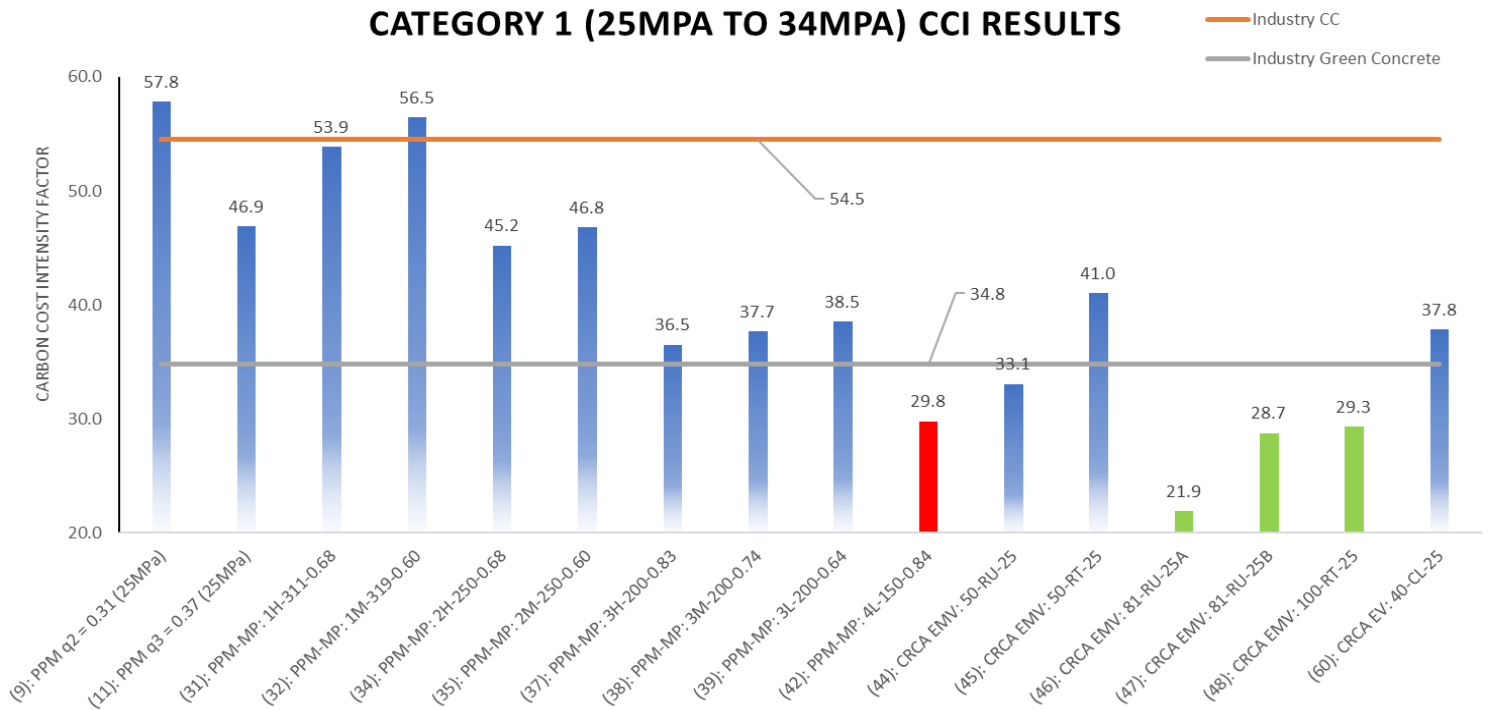


Figure 32 - Carbon Cost Intensity Factor Results for Category 1 (25MPa to 34MPa)

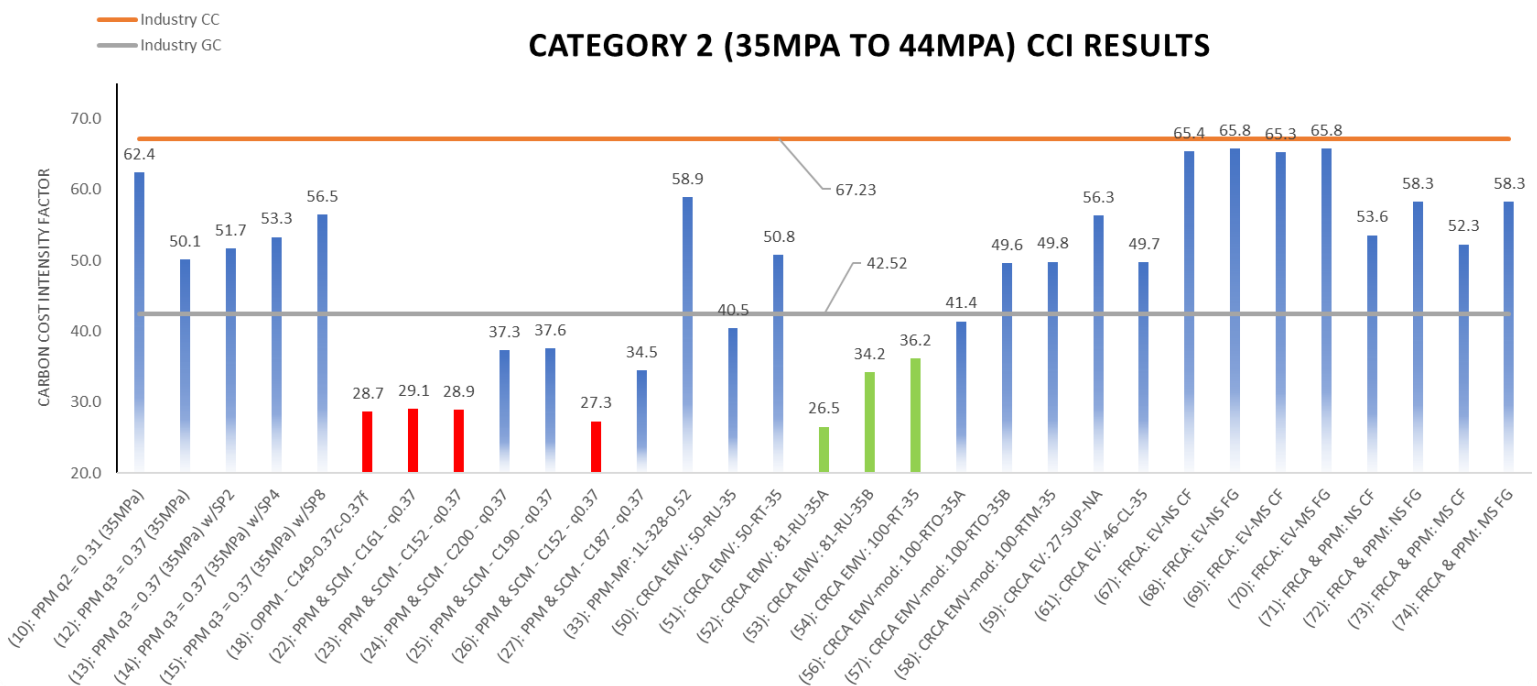


Figure 33 - Carbon Cost Intensity Factor Results for Category 2 (35MPa to 44MPa)

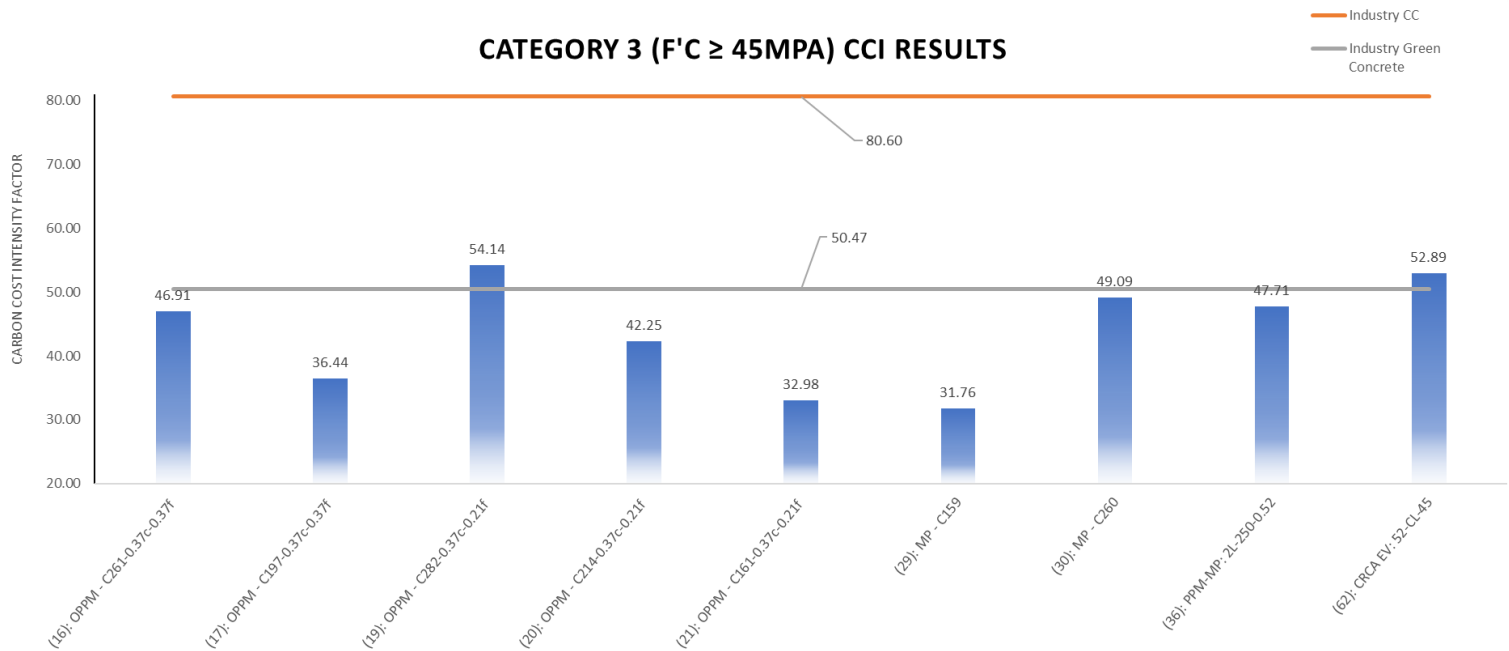


Figure 34 - Carbon Cost Intensity Factor Results for Category 3 (F'c ≥ 45MPa)

The CCI factor was structured to be cost multiplied by the global warming potential to ensure the goal remains to reduce both costs and GWP. Had the formulation been similar to the carbon intensity factor where the GWP is divided by the coefficient (cost in this case), then a lower CCI factor would have incentivized higher cost to reduce the factor rather than trying to lower both costs and GWP.

### 3.4.2 Integrated Strength Cost Eco-Efficiency (I-SCEE) Coefficient

The second relationship developed as part of this work is an integrated coefficient between concrete compressive strength ( $f'c$  expressed in MPa), cost (expressed in  $\$/m^3$ ), and environmental impact (expressed as GWP in  $Kg CO_2\text{-eq}/m^3$ ), and this coefficient has been named “Integrated Strength Cost Eco-Efficiency”. This coefficient combines the three main variables within this work into one coefficient and is considered an improvement on the I-SEE coefficient [51] which only incorporated strength and GWP. The integrated strength cost ecoefficiency factor is represented in the following equation:

$$I - SCEE = \frac{I - SEE}{Cost} * 100 = \frac{f'c / GWP}{Cost} = \frac{\frac{(MPa)}{(\frac{Kg CO_2}{m^3})}}{(\frac{\$}{m^3})}$$

The concept behind the I-SCEE coefficient combines three main parameters within the concrete industry to provide designer and decision makers with the ability to specify performance, eco-efficiency, and economical requirements all as part of one parameter. Similar to the I-SEE concept, a higher I-SCEE coefficient corresponds

to a more efficient strength and environmental impact mix design as a function of cost whereas a lower I-SCEE coefficient corresponds to a less efficient strength and environmental impact mix design as a function of cost. The I-SCEE coefficient provides valuable data to ensure that the decision makers are aware of the cost of the performance and GWP requirements that the designers are specifying. There are many instances where owners of projects have been surprised with the cost of the work after the design and tendering process has been completed and had to go through value engineering exercises to reduce the cost of the work. The use of the I-SCEE coefficient, once well established, will become a well-known parameter within the concrete industry that owners and decision makers will be aware of when selecting concrete mix designs. This parameter also provides the ability for designers and specifiers to outline the performance requirements very simply which will then allow concrete suppliers to use innovative tools such as LCC mix designs to produce the most efficient mix at the best price point to meet the project requirements. The I-SCEE coefficient was evaluated for all the LCC mixtures as part of this work and presented in figures 35, 36, and 37 for low, normal, and high strength categories respectively. For low strength concrete (figure 35), mix #42 (PPM-MP) mix #46 (CRCA EMV) yielded the highest I-SCEE coefficients compared to all other mixtures which were 29% and 27% higher than industry GC respectively. For normal strength concrete (figure 36), OPPM, combined PPM/SCM, and CRCA EMV methods all yielded results higher than industry GC proving that they are more efficient than industry GC from a combined performance, eco-efficiency, and cost approach. For high strength concrete (figure 37), all mixtures except one yielded results higher than industry GC from 3% up to 55%.

### CATEGORY 1 (25MPA TO 34MPA) I-SCEE RESULTS

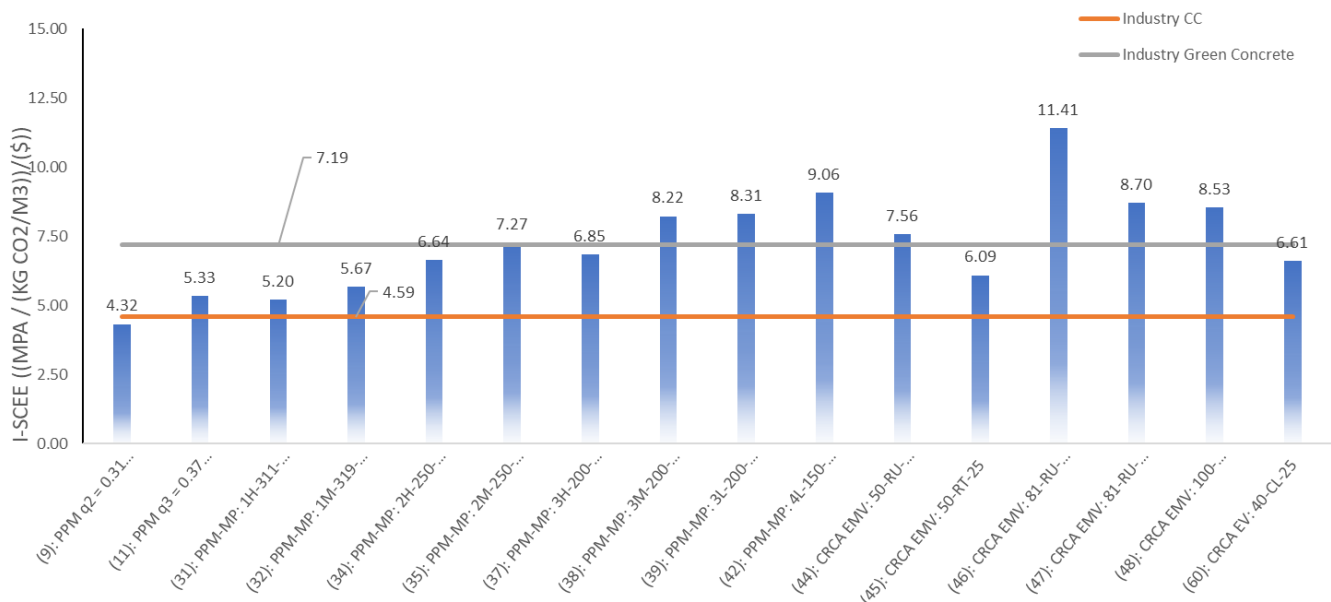


Figure 35 - Integrated Strength Cost Eco-Efficient (I-SCEE) Coefficient Results for Category 1 (25MPa to 34MPa)

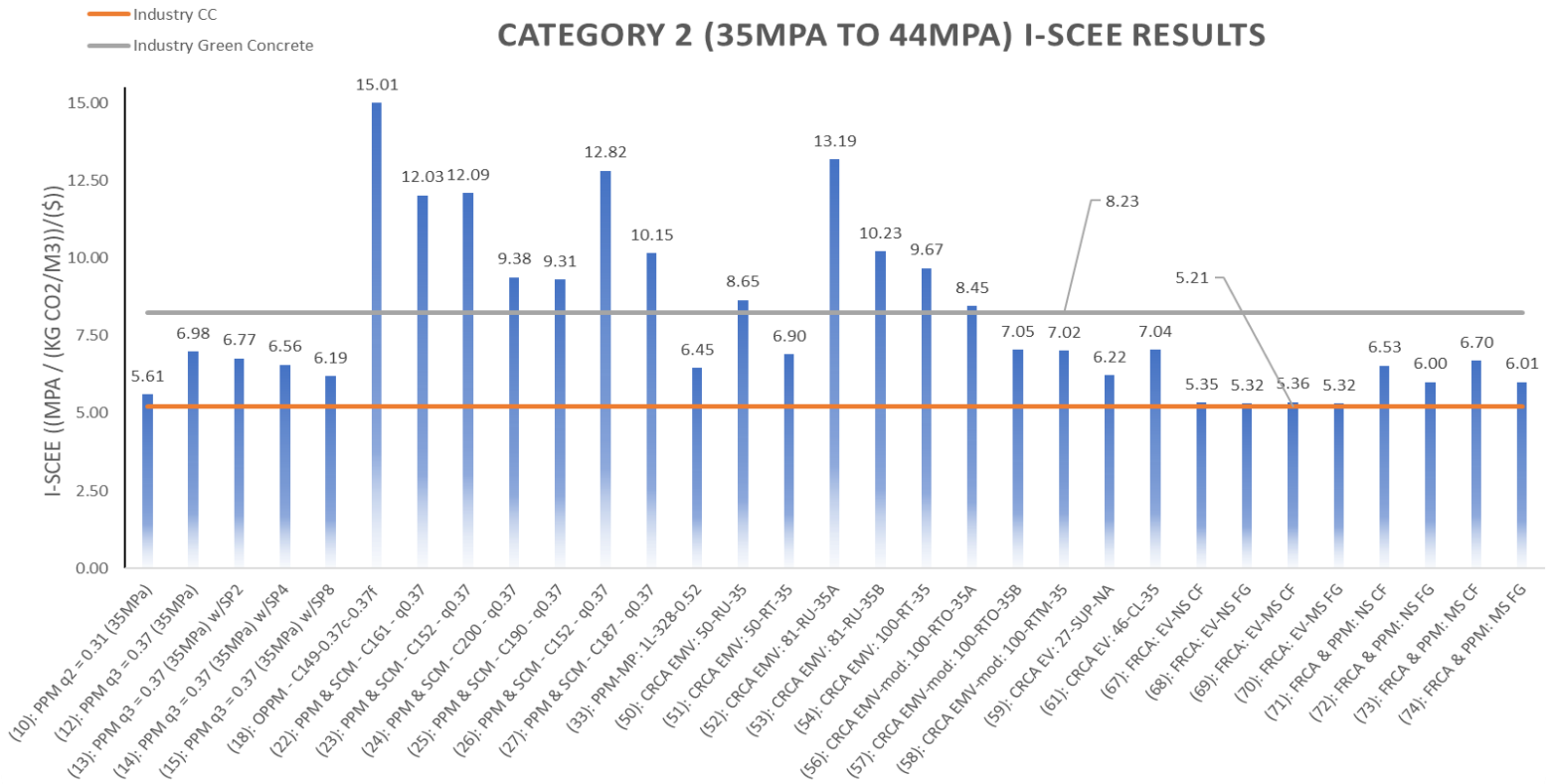


Figure 36 - Integrated Strength Cost Eco-Efficient (I-SCEE) Coefficient Results for Category 2 (35MPa to 44MPa)

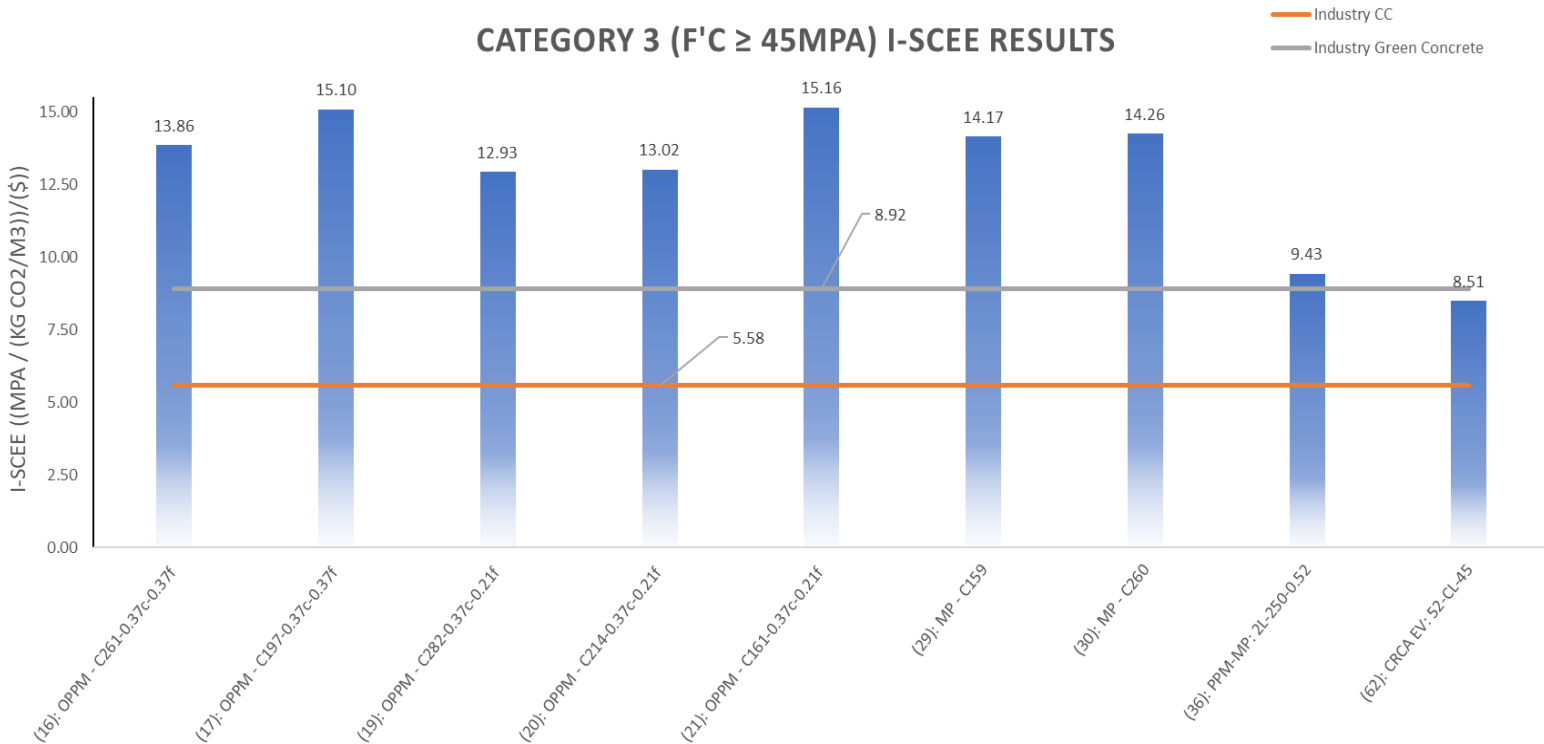


Figure 37 - Integrated Strength Cost Eco-Efficient (I-SCEE) Coefficient Results for Category 3 (F'C ≥ 45MPa)

### 3.5 DISCUSSION

The research program was developed to address and fill a gap within the industry body of knowledge on the influence of sustainable concrete mix designs on overall cost and global warming potential. The three pillars of sustainability are Environmental, Social, and Economical; and researchers around the world have focused on the environmental and social implications of these mix designs by evaluating their fresh and hardened state properties but little research was completed on their economical impact. This study was the first step part of a lifecycle analysis of these mixtures and the results have shown that the use of advanced mix design techniques (LCC such as PPM's & MP's; and RCA such as use of EMV, EV, etc.) either individually or in combination have yielded superior results compared to industry CC & GC. These results will only be further complemented with further life cycle analysis research as the hardened state and durability properties of these LCC mixtures are proving to be more robust than industry CC & GC.

The industry's current approach to eco-efficiency in concrete mix designs (use of SCM's as replacement to PC) is not sustainable long term as SCM availability is depleting and therefore the use of advanced mix design techniques is required. The other concern with the industry's current approach is that the GWP of SCM's can vary greatly depending on the production method and region; for example, some datasets from the United States and Canada show slag, fly ash, and silica GWPs as high as 0.39, 0.15, and 0.53 kg CO<sub>2</sub>eq/ kg of material, respectively. The varying GWP of SCM's makes the material not reliable in all regions/applications and therefore the focus needs to remain on developing and enhancing advanced mix design mixtures using innovative approaches such as PPM's/MP's for LCC and EMV/EV for RCA.

The use of cost evaluation as a selection indicator can be misleading if used on an individual basis as costs are always able to be reduced but performance and GWP will also always be affected. The same applies for selection based GWP reduction, eco-efficiency can always be improved but performance and cost will be impacted. It is important to evaluate the economic impact in conjunction with performance properties and environmental impact. This study assessed the cost and GWP of various mixtures and found that to lower both below industry standards, a more advanced mix design approach is necessary. Basic approaches tended to yield similar or higher costs than industry standards, but mixtures using advanced materials like LCC and RCA, combined with advanced methods, reduced costs and GWP compared to industry CC & GC. The cost of a concrete mix is significantly influenced by its fresh state behavior, a variable that wasn't thoroughly examined in the comparison of mixtures. The fresh state behavior of each mixture is still being studied rheologically, leaving uncertainty about their suitability for various applications. Integrating fresh state behavior into the costing metrics used in this study is necessary for future improvements.

### 3.5.1 High Sustainable Mix Designs Review

In this work, mix designs are appraised as high in sustainability when they surpass the indicators of industry green concrete (baseline mixtures). All advanced concrete mixtures were separated into three different categories: 1) low strength ( $f'c = 25\text{MPa}$  to  $34\text{MPa}$ ); 2) normal strength ( $f'c = 35\text{MPa}$  to  $34\text{MPa}$ ); and 3) high strength ( $f'c \geq 45\text{MPa}$ ), each of these mixtures had varying levels of sustainability based on the different parameters evaluated. The use of advanced concrete mix design techniques did not provide promising results in the low strength category as industry GC yielded more consistent I-SEE, CCI, and I-SCEE results, and for this reason the review of the low strength category has been omitted from this section. The recommendation of this work is to use industry GC over advanced mix design techniques for low strength concrete until further research/improvements is completed on the low strength category.

In the normal-strength category, 10 of 31 advanced concrete mixtures yielded promising results compared to industry GC in majority of the indicators and the results are presented in figure 38. The 10 “highly sustainable” mixtures are a result of three main techniques: LCC-OPPM, LCC-PPM/SCM, and CRCA-EMV. The most interesting parameters to compare are I-SEE (which is the inverse of  $C_i$ ), CCI, and I-SCEE as they each show different correlations between cost, performance, and environmental impact. OPPM mixtures as part of the LCC materials represents superior I-SEE & I-SCEE results which means this mix proportion technique yields the most sustainable proportioning ensure efficiency in cost and carbon footprint while maintaining high performance. OPPM mixtures yielded a I-SCEE result up to 82% higher than industry GC, CCI result up to 15% lower than industry GC, and I-SEE result up to 38% higher than industry GC. The combination of PPM and SCM was expected to yield strong results since we are combining a well-established industry standard as well as a highly innovative packing model and the results yielded up to a 56% increase in I-SCEE, 19% reduction in CCI, and 39% increase in I-SEE compared to industry GC. The coarse RCA material using with EMD method yielded superior I-SEE and I-SCEE results, but mediocre CCI results due to the relatively higher amount of binder still present in the system and therefore higher GWP for every dollar spent.

In the high strength category, 8 of 9 mixtures yielded promising results compared to industry GC as presented in figure 39. It is evident that for high strength mixtures, advanced mix design techniques (specifically LCC mixtures) are more sustainable than industry GC and therefore should be recommended in high-performance applications. Under this category, there was only one RCA mixture that did not show promising results but this finding is specific to this mixture and cannot be considered as a general finding since only one RCA above 45MPa was evaluated. Further review is required into high strength RCA mixtures to provide a more generalized conclusion.

CATEGORY 2 (NORMAL STRENGTH) MIXTURES - BI / CI / I-SEE / CCI / I-SCEE COMPARISON

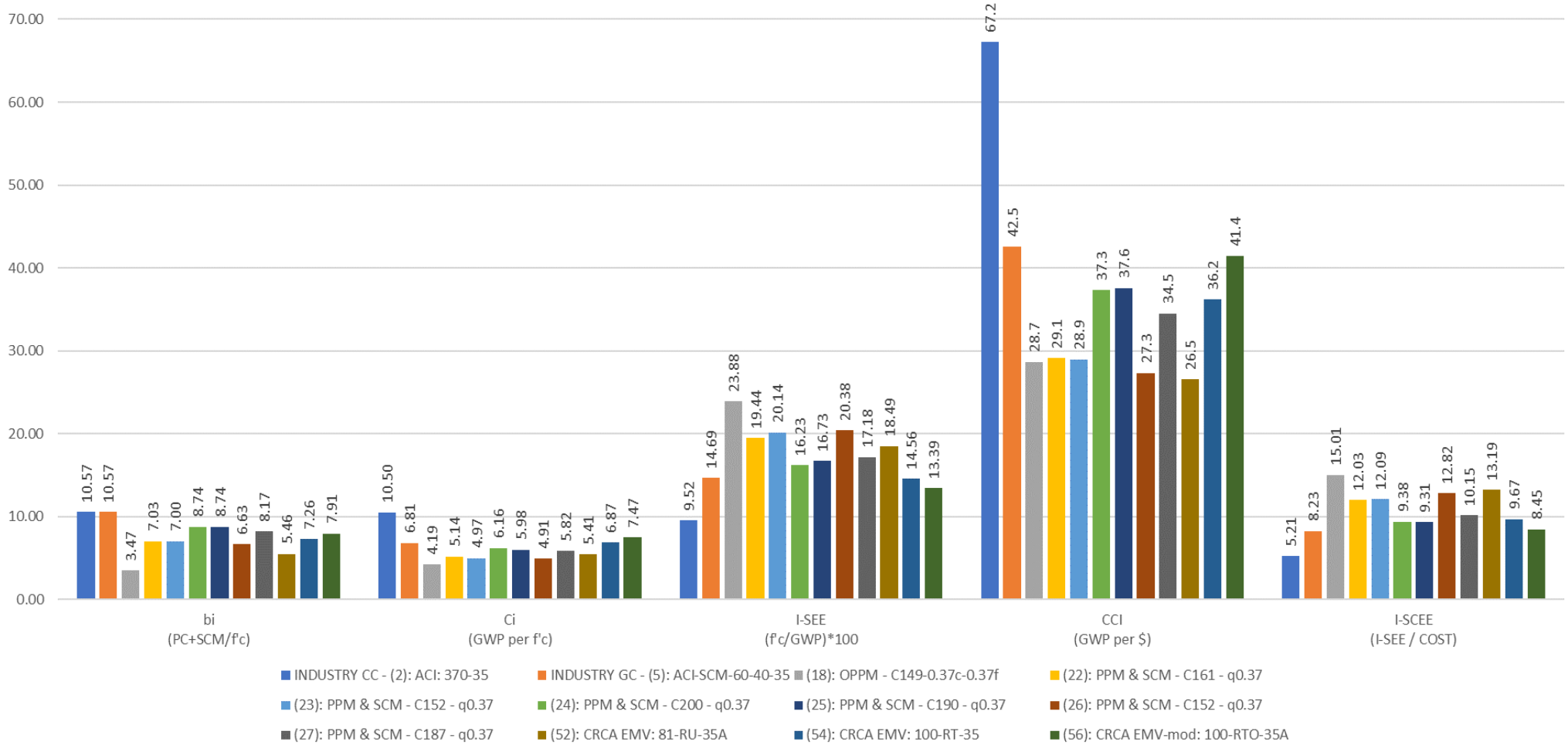


Figure 38 - Category 2 (Normal Strength) Mixtures – 1) Binder Intensity, 2) Carbon intensity, 3) Integrated Strength Eco-efficiency, 4) Carbon Cost Intensity, 5) Integrated Strength Cost Eco-Efficiency Comparison

CATEGORY 3 (HIGH STRENGTH) MIXTURES - BI / CI / I-SEE / CCI / I-SCEE COMPARISON

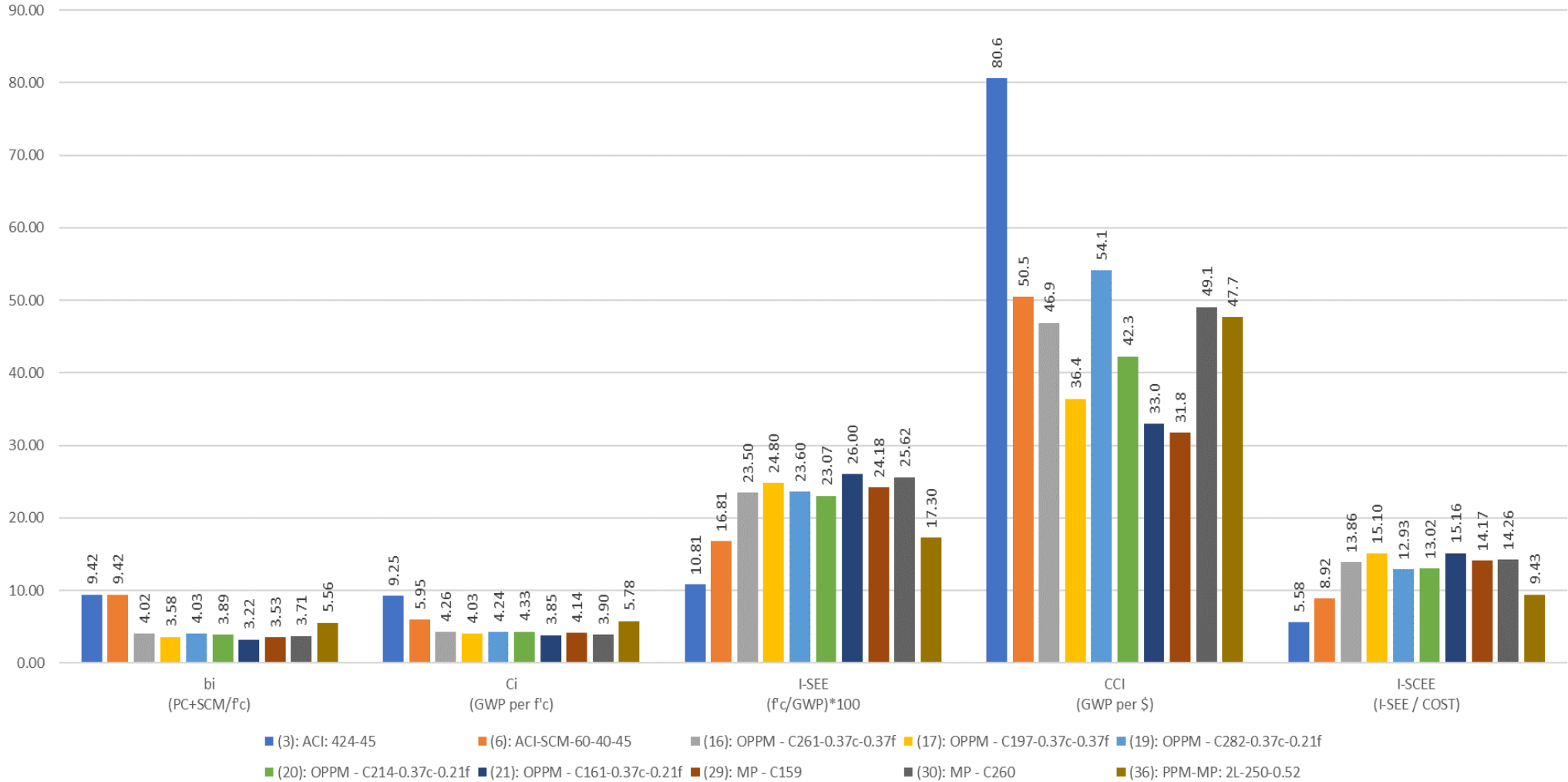


Figure 39 - Category 3 (High Strength) Mixtures – 1) Binder Intensity, 2) Carbon intensity, 3) Integrated Strength Eco-efficiency, 4) Carbon Cost Intensity, 5) Integrated Strength Cost Eco-Efficiency Comparison

### 3.5.2 Carbon Cost Intensity (CCI) Factor

The carbon cost intensity factor is a new proposed design parameter that is beneficial in applications where the goal is evaluate and drive down the cost and carbon footprint of a concrete mixture while the performance of the concrete is specified separately. In many cases within the industry, mixtures that are more eco-efficient are being priced at a high range and therefore this factor can be used by owners/designers to control both the cost and eco-efficiency of a concrete mixture for different applications while still specifying the performance requirements separately. This factor can also vary based on the importance and/or quantity of the structural element to ensure that elements of high frequency within a concrete structure are specified to receive a cost and eco-efficient concrete mixture. The CCI factor, while simple, is a valuable parameter for governments and decision makes to understand the impact to the CO<sub>2</sub> emissions in Kg/m<sup>3</sup> for every dollar spent. The government of Canada can use this parameter as a baseline for the amount of dollars that need to be spent on sustainable concrete mixtures to ensure they reduce the targeted number of emissions within concrete construction. CCI results for the “highly sustainable” mixtures are shown in figures 38 and 39. The original formulation of the CCI factor was structured to be GWP divided by cost (similar to the concept of carbon intensity but using cost in lieu of compressive strength), but this formulation incentivized higher cost to reduce the CCI factor rather than trying to lower both costs and GWP which is why the formulation was revised to be cost multiplied by GWP.

The current formulation of the CCI factor suggests that the weight (importance) of the cost & GWP are the same since they are both raised to the power of one but this may not be the case under different applications. The weight (importance) of these different parameters is dependant on the requirements/specifications identified by the end-user. An analysis should be completed by the end-user to determine the weights of these factors and this can be adjusted in the CCI formulation. If the end-user’s goal is maximizing cost efficiency while maintaining an acceptable eco-efficiency, then the weight of the cost parameter will be higher than the GWP parameter in the CCI evaluation, and vice versa. Generally for public sector clients such as governments, since there are high standards for eco-efficiency, maximizing eco-efficiency may be considered to be more important than cost efficiency and therefore a higher weight can be applied in the CCI formulation.

### 3.5.3 Integrated Strength Cost Eco-Efficiency (I-SCEE) Coefficient

The Integrated Strength Eco-Efficiency parameter is beneficial in research and/or mix design analysis applications where the goal is to compare the overall sustainability of a mixture through cost efficiency, carbon efficiency, and performance. The I-SCEE coefficient can be used in applications where a decision maker is selecting a mix

design from multiple different suppliers and the criteria is cost efficiency, strength performance, and carbon eco-efficiency. When comparing the different mixtures shown in figures 38 & 39, the evaluation of the I-SCEE showed different results compared to I-SEE results which are due to the incorporation of the cost of the mix into the evaluation. The incorporation of the cost parameter re-balanced the results and showed the true comparison between the different mixtures. For example, when comparing mixtures #24 & #25 (both PPM/SCM), the I-SEE parameter indicates that the mix #25 performs better, whereas the I-SCEE parameter indicates that mix #24 is better after incorporating the cost aspect. The same trend was realized for mixtures #19 and #20 between I-SEE and I-SCEE. Similar to the CCI factor, the I-SCEE factor is based on an equal weight (importance) for each of strength, GWP, and cost but this is not the case for different applications, therefore a study needs to be completed by the end-user to identify the importance of each of these parameters for their application and therefore different weight can be assigned for the I-SCEE evaluation.

### 3.6 CONCLUSION & RECOMMENDATIONS

The current work appraised the influence of advanced sustainable concrete mix design techniques on the cost of concrete mixtures and their global warming potential (GWP). Based on the results presented in this paper, the main conclusions are:

- The goal of this study is to not to review/analyze market variations and fluctuations on the cost & GWP but rather the impact of mix proportioning of sustainable methods on cost & GWP.
- For low strength concrete ( $f'c = 25\text{MPa}$  to  $34\text{MPa}$ ): Industry GC Using SCM's yielded more promising and consistent cost & GWP results than most advanced mix design techniques which proves that the impact of advanced mix design techniques is higher on normal strength and high strength concrete which are typically used in structural applications. Although there were 6 mixes that have a lower cost when compared to industry GC, only two of them resulted in lower than GWP compared to industry GC. The same trend is evident from the I-SEE, CCI, and I-SCEE results.
- For normal strength concrete ( $f'c = 35\text{MPa}$  to  $44\text{MPa}$ ): Three mix design techniques stood out compared to industry GC and have promising potential to achieve better LCA results: OPPM (mix #18), combined PPM/SCM (mix #26), and CRCA EMV (mix #52). These three mixtures yielded I-SCEE results in the range of 56% to 82% higher than industry GC and 146% to 188% higher than industry CC.
- For high strength concrete ( $f'c \geq 45\text{MPa}$ ): Majority of advanced mix designs (LCC not RCA) yielded better results compared to industry CC & GC; proving that for the high strength category, advanced LCC mix

design techniques should always be employed. I-SCEE results ranged from 6% to 70% higher than industry GC for all mixes except one which was the RCA mix.

- The evaluation of cost and GWP individually for the concrete mixtures without consideration of performance or other parameters can be misleading and may lead to incorrect mix design selection for the required application, therefore two new parameters were established as part of this work to address this concern.
  - a. First parameter was established to simultaneously assess cost and eco-efficiency: “carbon cost intensity” (CCI) factor. This parameter is beneficial in applications where the goal is evaluating the cost and carbon footprint of a concrete mixture while the performance can be specified separately.
  - b. Second parameter was established to simultaneously assess concrete’s performance, economic impact, and environmental impact using a “Integrated Strength Cost Eco-Efficiency” (I-SCEE) coefficient. This parameter is beneficial in applications where optimum performance, cost, and carbon footprint are required.
  - c. The use of the CCI factor is more applicable within the industry as the performance of the concrete is typically specified separately for the different applications whereas the I-SCEE factor is more applicable within the research world as this parameter will help compare between different concrete mixtures that are being evaluated.
- After conducting this study, further investigations can be drafted, as presented hereafter (refer to chapter 5 for a more detailed list of future recommendations)
  - a. Incorporate the fresh state behavior in the cost assessment as the evaluation as part of this study did not consider the workability within the calculations.
  - b. Incorporate more performance indicators (fresh state, hardened state, durability) into the integrated coefficients for better evaluation and comparison between the mixtures.
  - c. Continue the life cycle assessment for the advanced mix designs as part of this work to further evaluate their performance compared industry conventional concrete and green concrete. The next stages of the LCA are: construction stage process, use stage, end of lift stage, and afterlife.
  - d. The findings within this study are specific to the group of concrete mixtures evaluated and therefore further analysis is required for more concrete mixtures with varying changes within mix designs/materials to develop more general conclusions/findings.

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## CHAPTER 4: SUMMARY & CONCLUSION

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The research program was established to explore and address a knowledge gap in the industry regarding the impact of sustainable concrete mix designs on overall costs and their potential to reduce global warming. The three pillars of sustainability: environmental, social, and economic; form the foundation of this study. While significant attention has historically been given to the environmental and social aspects of these concrete mixes by analyzing their properties in both fresh and hardened states, their economic impacts have been less studied. This investigation represents an initial phase in a life cycle analysis of these mixtures. The findings indicate that employing advanced mix design techniques, such as Low Cement Concrete (LCC) methods like PPMs and MPs, and Recycled Concrete Aggregates (RCA) like EMV and EV, either separately or in tandem, leads to better outcomes compared to conventional industry methods (CC & GC). These advantages are anticipated to be further validated by ongoing research into the life cycle, particularly as the durability and hardened state properties of the LCC mixtures are demonstrating greater robustness than those of traditional industry mixes. The primary conclusions of this research are outlined below:

### **Significance of the shift to advanced concrete mix designs:**

- The industry's reliance on supplementary cementitious materials (SCMs) as substitutes for Portland cement is not sustainable due to decreasing SCM availability and the variable global warming potential (GWP) of SCMs, which differs based on production methods and regions.
- This inconsistency necessitates a shift towards developing and improving advanced concrete mix designs using innovative techniques like PPM's/MP's for LCC and EMV/EV for RCA.

### **Influence of Sustainable mixtures on low strength concrete ( $f'c = 25\text{MPa}$ to $34\text{MPa}$ ):**

- Industry GC Using SCM's yielded more promising and consistent cost & GWP results than most advanced mix design techniques which proves that the impact of advanced mix design techniques is higher on normal strength and high strength concrete which are typically used in structural applications.
- Although there were 6 mixes with a lower cost compared to industry GC, only 2 of them resulted in lower than GWP compared to industry GC. The same trend is evident from the I-SEE, CCI, and I-SCEE results.

### **Influence of Sustainable Mixtures on normal Strength Concrete ( $f'c = 35\text{MPa}$ to $44\text{MPa}$ ):**

- Three mix design techniques stood out compared to industry GC and have promising potential to achieve better LCA results: OPPM (mix #18), combined PPM/SCM (mix #26), and CRCA EMV (mix #52). These three mixtures yielded I-SCEE results in the range of 56% to 82% higher than industry GC and 146% to 188% higher than industry CC.

### **Influence of Sustainable Mixtures on high Strength Concrete ( $f'_c \geq 45\text{MPa}$ ):**

- Majority of advanced mix designs yielded better results compared to industry CC & GC; proving that for the high strength category, advanced mix design techniques should always be employed compared. I-SCEE results ranged from 6% to 70% higher than industry GC for all mixes except one.
- In the high strength category, the specific low cement concrete mix designs (OPPM / MP) performed and yielded better results compared to RCA mix designs. This statement cannot be generalized as there was only one RCA mixture as part of the high strength category.

### **Two New Design Parameters: Carbon Cost Intensity & Integrated Strength Cost Eco-Efficiency**

- The evaluation of cost and GWP individually for the concrete mixtures without consideration of performance or other parameters can be misleading and may lead to incorrect mix design selection for the required application, therefore two new parameters were established as part of this work to address this concern.
  - a. First parameter was established to simultaneously assess cost and eco-efficiency: “carbon cost intensity” (CCI) factor. This parameter is beneficial in applications where the goal is evaluating the cost and carbon footprint of a concrete mixture while the performance can be specified separately. The CCI factor, while simple, is a valuable parameter for governments and decision makers to understand the impact to the CO<sub>2</sub> emissions in Kg/m<sup>3</sup> for every dollar spent. The government of Canada can use this parameter as a baseline for the amount of dollars that need to be spent on sustainable concrete mixtures to ensure they reduce the targeted number of emissions within concrete construction.
  - b. Second parameter was established to simultaneously assess concrete’s performance, economic impact, and environmental impact using a “Integrated Strength Cost Eco-Efficiency” (I-SCEE) coefficient. This parameter is beneficial in applications where optimum performance, cost, and carbon footprint are required. The I-SCEE coefficient can be used in applications where a decision maker is selecting a mix design from multiple different suppliers and the criteria is cost efficiency, strength performance, and carbon eco-efficiency.
- The use of the CCI factor is more applicable within the industry as the performance of the concrete is typically specified separately for the different applications whereas the I-SCEE factor is more applicable within the research world as this parameter will help compare between different concrete mixtures that are being evaluated.

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## CHAPTER 5: RECOMMENDATIONS FOR FUTURE WORKS

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After conducting this study, further investigations can be drafted, as presented hereafter:

- Incorporate the fresh state behavior in the cost & GWP assessment as the evaluation as part of this study did not consider the workability within the calculations.
- Incorporate more performance indicators (fresh state, hardened state, durability) into the integrated coefficients for better evaluation and comparison between the mixtures.
- Continue the life cycle assessment for the advanced mix designs as part of this work to further evaluate their performance compared industry conventional concrete and green concrete. Begin by expanding the system boundary from cradle to gate to cradle to grave which includes the following:
  - **Construction stage process:** transport to building site and installation into building/structure.
  - **Use Stage:** Investigate the long-term maintenance needs of structures built with sustainable concrete versus traditional concrete. This includes assessing the frequency and cost of repairs, resurfacing, and protective coatings over the structure's lifespan. Sustainable concrete mixes might reduce these costs due to their potential for enhanced durability and resistance to environmental degradation.
  - **Energy and Resource Efficiency:** Consider the energy and resource efficiency during the operation phase of concrete structures. For instance, sustainable concrete with better thermal properties might lead to lower heating and cooling costs, adding to the overall lifecycle savings.
  - **End of Life Stage:** Evaluate the costs & GWP associated with the end-of-life phase of concrete structures, including demolition, waste disposal, and recycling. Sustainable concrete designs might offer cost benefits here, as they could be more easily recyclable or have lower environmental fees associated with their disposal.
  - **Afterlife:** Evaluate reuse and recycling of these materials such as RCA's
- Expand this study (cost and GWP assessment) into more concrete mixtures with wide variety of materials and mix designs to develop a more general understanding/finding. This study is very specific to a group of concrete mixtures and some findings may not be generalized since the mixtures used within this study are yet to be further optimized and improved under other ongoing studies.
- Complete study on the importance (weight) of the different parameters (cost, GWP, strength, etc.) under different applications so this can be incorporated into the formulations of CCI & I-SCEE.

- Many of the reputable concrete and cement production companies are deploying carbon capture, utilisation, and storage (CCUS) technologies where they are focusing on sequestration of high-purity CO<sub>2</sub> from the clinker production process which ultimately reduces CO<sub>2</sub> emissions that are released into the atmosphere. This process needs to be further reviewed and incorporated to understand its influence on cost & global warming potential for sustainable concrete mix designs.
- Complete a comparative analysis between sustainable (varying types) and conventional concrete:
  - **Durability and Longevity Considerations:** Sustainable concrete mixes are often designed to be more durable and resistant to weathering, chemical attack, and other forms of degradation. Quantify the economic & environmental benefits of this increased durability, such as extended service life and reduced need for repairs, and compare them with the traditional concrete that might require more frequent interventions.
  - **Environmental Impact and Associated Costs:** Factor in the costs related to environmental impacts, such as carbon pricing, fines, or incentives for low-carbon construction. Sustainable concrete with a lower global warming potential (GWP) might lead to savings in projects where carbon reduction is financially incentivized.
  - **Risk and Uncertainty Analysis:** Include a risk assessment in the lifecycle cost analysis to account for uncertainties related to long-term performance, material availability, and future regulations. Sustainable concrete might offer a hedge against future cost increases due to stricter environmental regulations or resource scarcity.
  - **Project-Specific Considerations:** Tailor the lifecycle cost analysis to specific types of construction projects. For example, infrastructure projects with long lifespans may benefit more from the durability of sustainable concrete, while residential projects might prioritize initial cost savings.
- Conduct sensitivity analyses to understand how changes in key variables, such as material costs, energy prices, and maintenance schedules, affect the overall lifecycle cost of sustainable versus traditional concrete. This helps in identifying the most cost-effective solutions under varying conditions.

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