EVALUATING EMBODIED CARBON AND CIRCULARITY IN CONSTRUCTION: A CASE STUDY OF CONCRETE DATA FROM 65+ NORTH AMERICAN PROJECTS

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EVALUATING EMBODIED CARBON AND CIRCULARITY IN CONSTRUCTION: A CASE STUDY OF CONCRETE DATA FROM 65+ NORTH AMERICAN PROJECTS

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Esta tesis está dedicada a mis padres,
Por su apoyo incondicional, aliento y amor.

This thesis is dedicated to my parents,
For their unwavering support, encouragement, and love.

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LIST OF SYMBOLS AND ABBREVIATIONS

C&D	Construction and Demolition
CSI	Construction Specification Institute
EC	Embodied Carbon
EPD	Environmental Product Declarations
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ITZ	Interfacial Transition Zone
JV	Joint Venture
LCA	Life Cycle Assessment
LFI	Linear Flow Index
MCI	Material Circularity Indicator
MSW	Municipal Solid Waste
NA	Natural Aggregate
PCR	Product Category Rules
RCA	Recycled Concrete Aggregate
SCM	Supplementary Cementitious Materials
UNEP	United Nations Environment Programme
VOC	Volatile Organic Compound
WBLCA	Whole Building Life Cycle Assessment

SUMMARY

The built environment plays a significant role in climate change, contributing nearly 40% of global greenhouse gas (GHG) emissions—much of which stems from the materials used and ultimately discarded during construction and at building end-of-life. This thesis investigates the embodied carbon of building materials, with a focus on concrete, and explores how circular strategies can support carbon reduction in the commercial construction sector. Through a combination of industry analyses, select literature review, and the application of the Material Circularity Indicator (MCI), this research analyzes and evaluates both the embodied carbon intensity and circularity potential of concrete.

Results confirm that concrete is the largest contributor to embodied carbon in buildings. While circularity strategies, such as the use of recycled concrete aggregate (RCA), show some potential material benefits, they do not meaningfully reduce GHG emissions due to the dominant role of cement in concrete's carbon profile. Therefore, reducing embodied carbon in concrete requires a multifaceted approach that includes material substitution in cement and aggregate, design efficiency, and optimization of regional transportation logistics.

Overall, the present study emphasizes the value of industry-academic collaboration and transparent data sharing. Stronger partnerships among contractors, researchers, and policymakers are essential to expand life cycle assessments (LCA) practices, set benchmarks, and accelerate the construction industry's transition toward low-carbon and circular solutions.

CHAPTER 1. INTRODUCTION

Climate change is one of the most urgent challenges of society today, largely driven by carbon emissions from human activities, impacting societies across all continents. Climate change is considered a wicked problem—an enormously complex societal problem with no clear solution and no shared interest across stakeholders. The built environment plays a significant role in climate change effects, with the building sector being responsible for nearly 40% of global energy consumption and 30% of global greenhouse gas (GHG) emissions (United Nations Environment Programme, 2024). The building sector produces two types of emissions: operational carbon—emissions derived from building operations—and embodied carbon—emissions associated with the remainder of a building's life cycle (e.g., raw material acquisition and end-of-life disposal pathways).

In recent decades, significant strides have been made toward reducing operational carbon in the construction industry. This is because operational carbon—emissions associated with energy use during a building's occupation phase—has been the most apparent contributor to a building's total carbon footprint (Ibn-Mohammed et al., 2013). With an operational phase that spans decades, versus short construction and end-of-life phases that last months to a couple of years, operational carbon has become a clear focus of research and mitigation strategies in the construction industry. However, this emphasis on the operational phase has left embodied carbon—emissions associated with building materials, construction processes, and disposal—being largely overlooked.

This is increasingly problematic, as it overlooks the growing share of embodied carbon within the total GHG emissions of buildings. As buildings become more energy efficient and grid systems decarbonize, embodied carbon is expected to account for the majority of total carbon emissions from global new construction between now and 2030. (*Why The Built Environment – Architecture 2030*, n.d.). In fact, the carbon footprint of new buildings will be dominated by embodied impacts due to material manufacturing and construction activities (*Why The Built Environment – Architecture 2030*, n.d.). This challenge is amplified by the pace of development: between now and 2060, the world is projected to double its building floor area—which is equivalent to constructing an entire New York City every month for 40 years ("The Carbon Challenge," n.d.). Without meaningful intervention, much of the emissions associated with this unprecedented growth will be locked in before a building is ever occupied.

At the same time, the concept of material circularity has recently emerged as a way to minimize resource depletion, reduce material waste, and extend the lifespan of products and materials. It is based on the principles of reuse, recycling, repurposing, and material reduction (Amarasinghe et al., 2024). While it may seem intuitive that this approach works in complete synergy with reducing embodied carbon, effectively integrating both circularity and embodied carbon concepts does not always align. For instance, efforts to reduce emissions may not always support material reuse strategies (Joensuu et al., 2022).

The following thesis explores the relationship between embodied carbon and circularity, focusing on concrete as the primary material of the study. Given that concrete is widely regarded as one of the greatest contributors to embodied carbon among building materials, this research seeks to validate this claim by utilizing a large dataset of

commercial industry projects. The main goal of the present study is to develop and provide key built environment stakeholders with a structured, formula-based approach for evaluating material selection. I will do this by analyzing varying levels of recycled content in concrete and its effects on embodied carbon intensity. Ultimately, this will allow decision makers, researchers, practitioners, and pertinent community stakeholders to weigh the trade-offs between sustainability and performance in this regard.

CHAPTER 2. BACKGROUND

2.1 The Climate Crisis and Carbon Emissions

Whether termed "global warming" or "climate change," the evolving shifts in Earth's climate system due to human activity is widely recognized (*Whats in a Name? Global Warming vs. Climate Change | Precipitation Education*, n.d.), with substantial evidence indicating its profound and far-reaching consequences for both natural and human systems (Rockström et al., 2009). The term "global warming" first gained prominence in the late 20th century, after it was first used in geochemist Wallace Broecker's 1975 Science journal article titled "Climatic Change: Are we on the Brink of a Pronounced Global Warming?" (*Whats in a Name? Global Warming vs. Climate Change | Precipitation Education*, n.d.). This "global warming" phrase was used to describe the observed increase in Earth's average surface temperature due to rising levels of greenhouse gases (GHG). However, as scientific research evolved, it was gradually recognized that the effects of human-induced emissions extend beyond escalating temperatures. Consequently, the term "climate change" emerged to encompass both the concept of global warming and the broader range of environmental impacts which GHG emissions trigger within the Earth's climate system and regulatory processes. Today, climate change is observed not only as an increase in Earth's average surface temperature but also in the shift of precipitation patterns, sea level rise, ocean acidification, and extreme weather events (Rockström et al., 2009).

Generally, Earth's climate is regulated by a complex interchange of natural processes, including variations in Earth's orbit and rotation, volcanic activity, ocean

current patterns, and the carbon cycle, which facilitates the exchange of carbon between sources and sinks to sustain atmospheric balance. However, these processes usually operate over extended periods of time, requiring tens of thousands of years to reach equilibrium. With the rapid expansion of civilization and industrialization that began in the 1800s, vast quantities of carbon dioxide (CO_2) and other GHG emissions have been released from geological reserves that formed millions of years ago through fossil fuel combustion (*You Asked*, 2019). This large-scale release has effectively compressed millions of years of natural processes into just decades and centuries. The unprecedented emission of gases has disrupted the Earth's natural carbon cycle, overwhelming its regulatory mechanisms and driving changes in the climate at an accelerated rate and in unpredictable patterns (US EPA, 2021) (*You Asked*, 2019).

In the year 1988, as climate science became more widely accepted, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) decided to create the Intergovernmental Panel on Climate Change (IPCC). The purpose of the IPCC was to provide policymakers with scientific assessments on climate change, describe its implications and potential future risks, and report on adaption and mitigation options. The organization perseveres today, and it has greatly contributed towards the understanding of climate change (*IPCC — Intergovernmental Panel on Climate Change*, n.d.). Notably, one of the IPCC's key achievements comes from its 2018 special report "Global Warming of 1.5C," which concluded that 0.5 degree of additional warming would mean substantially widespread poverty, extreme heat, sea level rise, habitat and coral reef loss, and drought (IPCC, 2022).

2.2 Buildings and Embodied Carbon

The potential consequences of a climate crisis and the effects it has already triggered on the natural environment have prompted an extensive examination of the possibility and strategies of reducing anthropogenic GHG emissions. Remarkably, the built environment and accompanying construction industry have a large role to play in global GHG emissions. In fact, UNEP's 2024 Global Status Report for Buildings and Construction found that buildings significantly contribute to climate change, accounting for about 37% of GHG emissions in 2022 (United Nations Environment Programme, 2024). These emissions stem primarily from building operations and the production of construction materials.

A building's total carbon footprint can be evaluated through a scientific approach called Life Cycle Assessment (LCA). LCAs can be used to evaluate environmental impacts across the entire life cycle of a product or service—from cradle to grave (Matthews et al., 2014). In emerging applications, LCAs have also been adapted to evaluate social and economic impacts in what are known as social LCAs (S-LCAs), and Life Cycle Cost Analysis (LCCA), respectively (Matthews et al., 2014) (Bozeman III et al., 2023) (*Social Life Cycle Assessment (S-LCA) - Life Cycle Initiative*, 2013). While LCAs can assess a wide range of social, economic, and environmental impacts—such as resource depletion, air and water pollution, and human health risks—in the context of buildings and as defined by the BS EN 15978 standard used in this thesis, LCAs are focused solely on environmental impacts. Within the built environment, this has primarily included GHG emissions due to their contribution to climate change (*Why The Built Environment – Architecture 2030*, n.d.). As such, while this thesis focuses on GHG emissions as the primary environmental

indicator, it acknowledges that other environmental impacts assessed through LCA may also be relevant – particularly in discussions around material circularity.

Building emissions can be categorized into two types: operational and embodied carbon. Operational carbon refers to the emissions associated with energy consumption during the building's use phase, and it includes elements such as space and water heating, cooling, lighting, and the operation of equipment and appliances (*Life Cycle Stages in Construction Works as per BS EN 15978*, 2023). On the other hand, embodied carbon encompasses the emissions generated from all other activities related to the assembly of a building, including material production, transportation, construction, and eventual demolition and disposal (*Life Cycle Stages in Construction Works as per BS EN 15978*, 2023). In both contexts, the term "carbon" is used as a shorthand for all GHG emissions, which are converted into a single metric known as carbon dioxide equivalent (CO_2e) to enable standardize comparisons (EPA, n.d.)

The British Standard BS EN 15978:2011 Sustainability of Construction Works is a widely recognized standard that provides a framework for assessing the environmental effects of buildings and construction works. This standard helps to ensure consistency, comparability among the research community, and categorizes a building's life cycle into four stages: Product (A1-A3), Construction (A4-A5), Use (B1-B7), and End-of-life (C1-C4) (*Life Cycle Stages in Construction Works as per BS EN 15978*, 2023). These four stages together represent a system boundary described as "cradle-to-grave."

Beyond the End-of-Life stage, there is an additional Beyond-the-Life-Cycle stage D that accounts for benefits beyond the life cycle system boundary—such as those achieved from reuse, recovery, and recycling. The full process is illustrated in Figure 1.

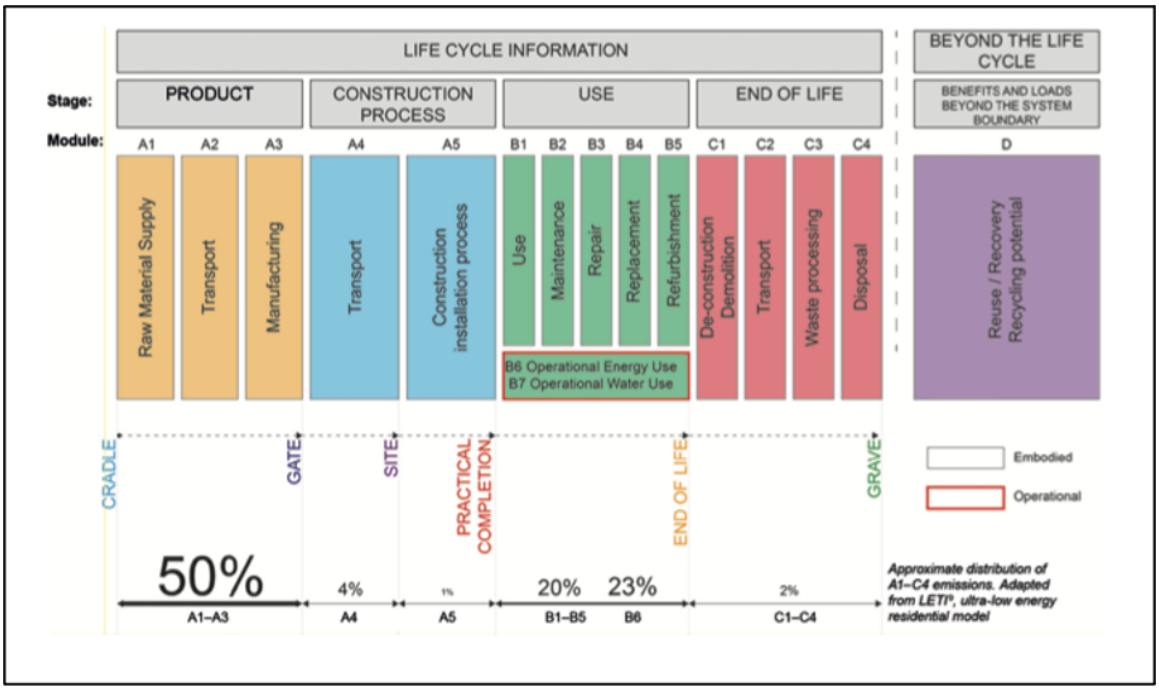

Figure 1 – Life Cycle Stages per BS EN 15978. From Life cycle stages in Construction works as per BS EN 15978: 2011, 2023, Structures Insider.

The Product stage of Figure 1, which can be captured in an LCA "cradle-to-gate" study boundary, includes all the activities involved in the production of building materials. This stage is divided into three modules: raw material extraction and processing (A1), transportation of raw materials to a manufacturing site (A2), and manufacturing of the final product (A3). The end of this stage is referred to as "the gate" because it marks the point at which the building material is ready to leave the factory for transportation to a construction site where it will be installed.

The Construction Process stage of Figure 1 is divided into two modules: the transportation of the building material from gate to site (A4), and the construction installation process (A5). The LCA emissions accounted for in this stage are generated by transportation activities, as well as energy consumption from on-site activities—such as the use of tools and machinery.

The Use stage of Figure 1 is the only phase in a building's life that includes both embodied and operational carbon. This stage includes the embodied impacts associated with component use (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5), as well as the emissions resulting from operational energy use (B6) and operational water use (B7) in the building. B1 accounts for emissions from materials that release volatile organic compounds (VOCs) or degrade over time. B2 and B3 cover GHG emissions generated by maintenance and repair activities, which involve material and energy use. B4 and B5 contribute to embodied carbon through the disposal of building components, material and equipment replacement, and renovation activities. While these emissions are often overlooked compared to the operational energy (*Why The Built Environment – Architecture 2030*, n.d.), they can be substantial; especially for long-lasting buildings that undergo continuous maintenance and renovation projects in order to extend their lifespan.

Once a building reaches the end of its useful life, it will eventually undergo disposal, whether through immediate deconstruction or after a prolonged period of abandonment. Nevertheless, as shown in Figure 1, the End-of-Life stage comprises deconstruction and demolition of building components (C1); transportation of material to landfill, incineration, or recycling facilities (C2); waste processing (C3); and final disposal

(C4). The end of this stage is referred to as “the grave” because it marks the end of intended use.

As depicted in Figure 1, GHG emissions from most stages in a building’s life cycle are considered embodied carbon, with only those associated with operational use (B6-B7) considered operational carbon. Given that the operational phase of a building lasts decades, while the product, construction, and end-of-life phases are comparatively shorter, it is clear why research and mitigation efforts have historically been focused on reducing operational carbon. This focus is also reinforced by the direct financial incentive for building owners and operators: reducing energy use during operation often results in immediate and measurable cost savings on utilities, whereas the impacts of embodied carbon are more abstract and further removed from day-to-day expenses. In the last few decades, the focus has been aimed toward designing and operating buildings more efficiently (Rockström et al., 2009), with the industry targeting net-zero carbon emissions during operation. To drive this goal, several regulations and initiatives worldwide have been introduced, including the Energy Policy Act (EPAct) of 2005 and ASHRAE Standard 90.1 in the USA, as well as the Minimum Energy Efficiency Standards (MEED) in the UK.

However, this building-operation focus addresses operational energy use and GHG emissions generated during the use phase and have not taken into consideration the remainder of the equation. Referring again to Figure 1, the schematic also illustrates the approximate distribution of A1-C4 emissions attributed to each life cycle phase, as adapted from the LETI Embodied Carbon Primer (*Embodied Carbon Primer*, n.d.). In this analysis, the share of carbon emissions for the Product stage (A1-A3) is shown as the most significant contributor, accounting for a total of 50% of total emissions. Following this,

operational energy use (B6) accounts for 23% of emissions, and the remaining Use phase activities (B1-B5) contribute 20%. While this distribution provides valuable insight into the relative importance of embodied carbon, it is based on generalized assumptions and typical building types from the UK (*Embodied Carbon Primer*, n.d.). As such, results may vary depending on regional construction practices, material choices, and operational energy sources. Nonetheless, this distribution underscores the importance of shifting focus from operational efficiency to addressing embodied carbon, since over 75% of the total GHG emissions for buildings come from those embodied carbon modules.

Therefore, addressing embodied carbon is essential to decreasing GHG emissions, since it increasingly represents a larger portion of a building's overall carbon footprint. As operational carbon emissions decrease due to improvements in design and system efficiency, embodied carbon becomes a more significant contributor to the building's overall lifecycle emissions.

2.3 Product Category Rules and Environmental Product Declarations

As understanding of the carbon impact of construction materials and processes grows, there is an increased demand for transparent and standardized environmental data from the construction industry. Product Category Rules (PCRs) have been created to define standardized methodologies for creating LCA studies, ensuring consistency and comparability when evaluating the environmental impacts of products with similar functions (*Product Category Rules (PCRs)*, n.d.). PCRs are developed openly and collectively by interested parties and stakeholders (e.g. material suppliers, manufacturers,

trade associations, LCA experts, and certification and regulatory bodies) (*Product Category Rules (PCRs)*, n.d.).

Built upon these PCRs, Environmental Product Declarations (EPDs) are developed, summarizing environmental impacts (*EPD Types & Their Uses | One Click LCA*, n.d.). EPDs often undergo a third-party verification. EPDs allow organizations to communicate their environmental footprint without sharing company or product-specific information. They can be categorized into Type I, Type II, and Type III depending on the ISO standards utilized. Each type varies by level of transparency, verification, and methodology. They are differentiated as follows (*What Are the Differences between Type I, Type II, and Type III Environmental Declarations?*, 2024):

1. **Type I Environmental Declaration (ISO 14024) – Ecolabels:** These are third-party environmental labels awarded to specific products after verification of environmental claims. Environmental criteria met by these products cover different categories, such as energy efficiency and emissions. Examples of such labels are Energy Star, EU Ecolabel, and Forest Stewardship Council (FSC) labels. While these labels may indicate a product meets certain sustainability criteria, they do not provide a full life cycle analysis.
2. **Type II Environmental Declaration (ISO 14021) – Self-declared Environmental Declarations:** Often, companies may declare their products meet certain environmental performances on their labels; however, they do not go through the process of having the claim independently verified (e.g. third-party verification). This type of environmental declaration includes statements such as “recycled content” and “low VOC emissions.” Due to its lack of verification and standardization, this type of

environmental declaration is considered less reliable and at risk of being used for greenwashing by companies.

3. **Type III Environmental Declaration (ISO 14025) – Environmental Product Declarations (EPD) based on full LCA:** This type of environmental declaration is created by conducting a full LCA on a product in accordance to the ISO 14025 standard, and presenting the detailed, quantified information on its environmental impacts. The reports are third-party verified to ensure standardization and transparency, which make it comparatively reliable.

Type III EPDs provide the most standardized, verifiable data currently available for analyzing embodied carbon in construction materials. They are often compared to nutrition labels for products because, like nutrition labels which provide detailed information about the nutritional content and ingredients of food, EPDs offer relatively transparent, objective reports that communicate a product's composition and its environmental footprint over its entire life cycle.

Furthermore, Type III EPDs can be classified into three categories: **product-specific EPDs,** which corresponds to the environmental impacts of a particular product; **project-specific EPDs**, which are created for a specific project and may vary in verification methods—some are internally verified, while others, such as those for curtainwall assemblies, may undergo third-party review depending on their intended use; and **industry-wide EPDs**, which aggregate data from multiple products within a specific sector to publish the average environmental footprint of the products.

EPDs also differ in their scope, depending on the life cycle stages they cover. A cradle-to-gate EPD only accounts for the emissions associated with raw material extraction, transportation, and manufacturing (A1-A3 emissions of Figure 1), which is the minimum required for an LCA. Conversely, a cradle-to-grave EPD covers the latter plus the emissions associated with installation, maintenance and end of life (stages A to C of Figure 1). Some EPDs may fall between the two ends of the spectrum, in what is referred to as "cradle-to-gate with options." These can include A1-A3 scopes along with selected downstream stages, such as installation (A5) or disposal (C4). This distinction is important to define as it affects the accuracy of contextually assessing a product's environmental impact.

Each type of EPD has a unique role in helping stakeholders make informed, sustainable choices, and facilitate the scaling of EPD adoption throughout the construction industry. Among the different types, industry-wide EPDs have proven to play a crucial role in enabling early-stage carbon accounting ("Embodied Carbon in Construction Calculator (EC3)," 2020). Since they provide generalized environmental impact data, industry-wide EPDs have been developed for common building materials. Due to their general nature, industry-wide EPDs can be utilized during preconstruction to estimate a project's carbon footprint before specific material procurement decisions are made. They can also be used in early-stage Whole Building Life Cycle Assessment (WBLCA) to inform systems-level decisions based on the rough order of magnitude (ROM) impacts of broad product categories—such as choosing between steel or concrete structural system – when detail product-specific data is not yet available ("Whole Life Carbon Assessment for Buildings and Construction Projects," n.d.). This capability helps project teams integrate

sustainability considerations into the decision-making process, ideally driving more conscious design and material choices.

2.4 LCA Databases and Tools

LCA databases and digital tools play a crucial role in supporting embodied carbon analysis by providing access to standardize environmental impact data for building practitioners. LCA databases are created as centralized repositories, compiling environmental data from various sources while simultaneously ensuring standardization and comparability. Sources may be primary, such as from manufacturers, as well as secondary, such as from literature. In order to be reliable and relatively accurate, these databases must be regionally sensitive, taking into consideration factors such as local manufacturing, technology, fuel source, and transportation methods (Hu & Esram, 2021).

There are a number of databases in existence, all of which vary in cost of use, region, data source, life cycle stage, and scope, including ecoinvent, GaBi, Athena, and EPD. Still, these databases are not without their weaknesses. That is, their standardization and transparency is often in need of improvement, as they are not regularly maintained and do not consistently include all required documentation on data sources and methodologies (Hu & Esram, 2021).

Building on these databases, software tools have been developed to streamline the application of LCA assessments in real-world projects. The tools generally integrate LCA data into material choices, often comparing materials, modeling alternative scenarios, and

aligning sustainability benchmarks. Current available tools in the U.S. include Athena, GaBi, Tally, Simapro, BEES, and EC3.

2.5 Circularity and the Material Footprint

One of the key challenges in assessing a building's life cycle environmental impact is the traditionally linear approach to its service life. Currently, a building's lifespan is largely based on the linear "extract-produce-use-dispose" model, which relies on the continuous exploitation of raw materials and leads to the irreversible disposal of waste at the end of life. This linear system places immense pressure on natural resources, which are being consumed faster than they can be regenerated, and excessive generation of waste, which may exacerbate air and water pollution, land degradation, and emissions of GHG gases and hazardous components.

In the construction sector, inefficiencies can lead to significant material waste. In fact, it has been estimated that as much as 30% of building materials delivered to a jobsite eventually go to into the waste stream, never even contributing to the structure (Osmani, 2011). On the other hand, construction and demolition (C&D) waste created during construction tends to only contribute about 10% of overall C&D waste (*Advancing Sustainable Materials Management: 2018 Fact Sheet*, n.d.). The remainder comes from demolition, indicating that end-of-life demolition is the largest driver for discarded materials. Overall, approximately 76% of C&D waste is recovered or recycled, effectively diverting it from landfills; however, this high diversion percentage does not

comprehensively eliminate the issue of waste (*Advancing Sustainable Materials Management: 2018 Fact Sheet*, n.d.).

In 2018 alone, C&D waste contributed nearly 145 million tons to U.S. landfills, accounting for approximately half of all landfill-bound waste that year. Despite the fact that total C&D waste levels outnumber municipal solid waste (MSW) 2-to-1, both streams contribute to landfills in nearly equal amounts. Altogether, C&D waste corresponds to about 20-40% of total solid waste stream globally, highlighting the ongoing challenge of waste management in the built world (Rodriguez-Morales et al., 2024).

Interestingly, the demolition of buildings is rarely ever due to structural failure or material durability. Instead, factors such as urban growth, functional obsolescence, and high renovation costs often incentivize demolition as the most favorable option (Manganelli et al., 2024). This suggests that buildings could remain in use longer; however, their design seldom accounts for end-of-life considerations. Most buildings are designed primarily to meet immediate needs, with only occasional foresight into future expansions or adaptions. In many cases, long-term flexibility is disregarded, and it results in structures being prematurely demolished once their initial purpose is fulfilled.

To address this issue, adopting circular design principles can help extend building lifespans and reduce unnecessary waste. Two key design approaches to achieving greater circularity in the built environment are designing for adaptability and circular material selection (Peña et al., 2021) (Kechidi, 2023). By incorporating modular layouts and adaptability for renovations, buildings can evolve with changing needs rather than become obsolete. Additionally, choosing reusable or recyclable materials can help ensure

components have viable end-of-life options, minimizing landfill disposal and supporting a more circular built environment.

In the BS EN 15978 life cycle stages schematic shown in Figure 1, Stage D, known as the Beyond-the-Life-Cycle stage, extends the traditional cradle-to-grave system boundary. This extension challenges the conventional linear process, which spans a building's life between raw material extraction and disposal. This stage introduces the potential for circular thinking by accounting for the potential benefits and burdens of material reuse, recovery, and recycling. By considering how materials can be repurposed or reintegrated into new construction or new useful products, the Beyond-the-Life-Cycle stage shifts the perspective of a finite life cycle toward a more regenerative and circular approach to building materials.

Materials used in the Construction stage require a significant amount of energy and raw resources to be manufactured. As discussed in the previous section, GHG emissions from this product stage alone can account up to 50% of a building's total life cycle emissions. When materials are discarded at the end of their life, not only is waste generated, but there is a system loss of embodied energy and carbon that was already invested in their production. Hence, the pursuit of circularity in materials is crucial. Circularity seeks to extend the life of materials through reuse, recycling, and repurposing, which ultimately reduces the need to further extract raw materials. Furthermore, keeping materials in use as long as possible maximizes the value of the impacts already incurred.

Nevertheless, the circular economy is not without its challenges. Many circularity strategies require significant processing, additional materials, and intensive energy inputs,

which can offset the intended environmental benefits in some cases (Joensuu et al., 2022). For example, recycling concrete can reduce the need for new aggregate, however, the reprocessing of concrete waste may require high amounts of energy and contribute to emissions. Similarly, designing for a recycled material, such as concrete, may demand additional structural considerations and elements due to differences in material integrity and features (Xiao et al., 2018). This approach may also increase upfront embodied carbon. Evidently, there are trade-offs between embodied carbon and circularity. While both may aim to reduce environmental impacts, they do not always align perfectly.

Consequently, this dilemma emphasizes the need for an optimization framework that balances embodied carbon considerations with circular strategies. By evaluating the full life cycle impacts of different materials and processes, designers and builders can make informed decisions that minimize overall environmental impacts while ensuring materials are utilized as efficiently as possible.

2.6 The Significance of Concrete

Concrete is the most widely used man-made material in the world, second only to water in terms of overall consumption (*About Cement & Concrete*, n.d.). Its durability, versatility, and strength has made it the dominant structural material in modern construction. However, its production comes with significant environmental consequences. Cement, the primary ingredient in concrete, is responsible for at least 8% of global carbon emissions, making concrete have be the most embodied carbon intensive building material (Belaïd, 2022). Given its predominance and high emissions, concrete is the focus material

of this study. I will, therefore, assess this material and its potential for reducing embodied carbon.

2.7 Purpose and Scope of Thesis

As the construction industry moves toward decarbonization, understanding the full carbon impacts of materials is essential. This includes not only accounting for the emissions generated from the demolition and disposal of concrete, but also recognizing the potential benefits of reducing embodied carbon through material circularity. Ideally, reusing and recycling concrete at the end-of-life and utilizing it in new concrete mixes can help offset raw material extraction and lower overall GHG emissions.

The purpose of this thesis is to evaluate embodied carbon in new construction by integrating academic research with industry data, and to assess whether circular strategies within concrete—such as incorporating recycled content—can meaningfully reduce embodied carbon impacts. Given that concrete is widely recognized as a major contributor to embodied carbon in buildings, this study focuses on analyzing how regional variations, project types, and circularity considerations influence the environmental carbon footprint of concrete in North American commercial construction.

To help meet this purpose, the research is guided by the following key questions:

1. What percentage of total embodied carbon in construction projects is attributed to concrete, and how does this vary across different project types and regional locations?

2. How does the incorporation of recycled concrete aggregate (RCA) influence embodied carbon calculations?
3. How can circularity metrics, such as material reuse and recycling potential at the end of life, be incorporated into embodied carbon assessments of concrete?

By addressing these questions, this research thesis aims to contribute to a more holistic understanding of embodied carbon in construction, emphasizing both life cycle and material circularity considerations. Furthermore, the results aim to provide industry insight that will inform design and procurement strategies that optimize both carbon reduction and circularity in building materials.

2.8 Thesis Structure

The following thesis is structured into several chapters, building upon one another to answer the three key research questions. **Chapter 3** presents a select literature review, offering a general overview of the current academic research, emerging trends, and intersection of embodied carbon and material circularity, with a particular focus on concrete. **Chapter 4** outlines the methodology of this study. It first introduces the industry data utilized in this study, detailing the source dataset and how embodied carbon information is collected. This chapter then describes the approach taken to answer each of the study's three research questions. **Chapter 5** presents the results obtained from the methodology, while **Chapter 6** provides a discussion on the key findings. Finally, **Chapter 7** concludes the thesis by summarizing key findings, acknowledging research limitations, and offering recommendations for future studies.

CHAPTER 3. SELECT LITERATURE REVIEW

3.1 Literature Scan Methodology

To establish the foundation for this research and contextualize the state of academic research surrounding "embodied carbon" and "circularity", a select literature search and review was conducted. The goal was to understand the current state of research and focus areas, compare research methodologies, and identify trends and gaps. The review process followed a structured approach to identify, collect, and analyze relevant research on embodied carbon and circularity in construction.

First, key research themes within the topic of embodied carbon were established to guide the review. These included **foundational theories and concepts**, **assessment methods**, **case studies**, **reduction strategies**, and **challenges and trends.** Since the research also aimed to evaluate material circularity, two additional themes were added under the topic of circularity, **circularity and embodied carbon** and **concrete circularity**.

A targeted search was conducted using Google Scholar and utilizing keywords and phrases such as "building embodied carbon", "carbon footprint in construction," "commercial construction life cycle assessment," and "embodied carbon and circularity." The search yielded thousands of relevant books, journals, and papers. The goal was to collect five to ten relevant papers for each of the previously established themes, so to establish a fundamental understanding for each. Hence, the first 15-20 search results were reviewed for initial relevance based on titles and generally limited to publications years of 2017 or later. However, exceptions were made for at least one publication within each

theme that predates this year-2017 threshold to help ensure I captured the historical emergence of each topic.

Once a paper was identified as potentially relevant, its abstract was reviewed. If the abstract provided meaningful context within one of the predefined themes, the paper was saved for further analysis. The full process resulted in the collection of 38 papers, which were then catalogued and categorized by theme in a spreadsheet. The full list is found in Appendix A.

Thereafter, each paper collected was reviewed with further detail, focusing on its methodology, results, and discussion to extract key findings. The following two sections synthesize these, presenting an overview of existing research within each established theme.

3.2 Overview of Embodied Carbon Research

For Embodied Carbon Research, Table 1 was created to present key highlights organized by these thematic categories: **foundational theories and concepts**, **assessment methods**, **case studies**, **reduction strategies**, and **challenges and trends**. Each theme serves to capture major insights that inform current understanding and future direction in addressing embodied carbon within construction and lifecycle practices.

Table 1 – Summary of Embodied Carbon Research by Theme

Foundational Theories and Concepts
Description: Articles grouped and reviewed under this category provide core concepts of embodied carbon and its significance.
Key Ideas: • Embodied carbon is becoming a dominant emission source globally. As operational energy use declines due to efficiency improvements, embodied carbon now accounts for up to 50% or more of a building's total life-cycle emissions. • Material production stages drive the majority of embodied carbon impacts. The A1-A3 stages consistently contribute the largest share of embodied emissions, particularly from carbon-intensive materials such as concrete and steel. • Life cycle thinking is essential for achieving net-zero goals, because true decarbonization in the build environment requires a whole-life carbon approach. • Benchmarking and databases are critical initiatives and innovative tools that have driven the understanding of material-specific carbon intensities; however, studies highlight there is a need for consistent data and reporting standards. • Lack of standardized definitions, boundaries, and metrics have led to significant data variability and limitations in comparability across studies and projects.

Table 2 continued

Assessment Methods
Description: Articles grouped and reviewed under this category summarize different methodologies used to assess embodied carbon in buildings.
Key Ideas: • There are three embodied carbon LCA approaches: process-based, input-output (I-O), and hybrid LCA methods. They each offer trade-offs between scopes and accuracy. • Methodological variables greatly influence research results, such as database selection, life cycle stages included, and • functional units. • Currently, design tools are focused in post-design stages; however, there is a demand for early-design tools that will support fast, low-data decisions. • Most assessments focus on A1-A3 (product) stages and exclude, A4-A5 (Construction), B (Use) and C (End-of-Life) stages.

Table 3 continued

Case Studies
Description: Articles grouped and reviewed under this category illustrate real-world applications, challenges, and results related to embodied carbon.
Key Ideas: • Structural materials, such as concrete and steel, are the primary contributors to embodied carbon in buildings across the board. • Timber structures typically demonstrate lower upfront embodied carbon due to carbon storage in wood; however, end-of-life scenarios can significantly affect net results. • Modular construction can reduce embodied carbon through reduction of concrete quantities, rebar, and optimized design. However, it can come with higher costs and material transportation impacts. • The regional context matters: local material supply chains, construction methods, and the local energy source can strongly influence embodied carbon results.

Table 4 continued

Reduction Strategies
Description: Articles grouped and reviewed under this category summarize strategies focused on the reduction of embodied carbon, including material selection, design optimization, and policy interventions.
Key Ideas: • Opting for low-carbon alternative structural materials – such as supplementary cementitious materials (SCMs) in concrete, recycled steel, and timber – can reduce embodied carbon by 20-60% depending on the substitution level. • Optimizing design can significantly reduce embodied carbon. Examples of this approach include right-sizing structural elements and incorporating design for manufacture and assembly (DfMA) or design for disassembly (DfD). • Modular and prefabricated systems reduce waste and carbon emissions through efficient material use and reduction of waste. • Building Information Modeling (BIM) and LCA integration enables iterative design feedback, allowing teams to evaluate material and design alternatives during early design stages. • Embodied carbon reductions are more likely to succeed when paired with client-driven targets, procurement incentives, and public policies.

Table 5 continued

Challenges and Trends
Description: Articles grouped and reviewed under this category discuss the challenges, limitations, and future trends in the field of embodied carbon.
Key Ideas: • Embodied carbon is underregulated despite its recognized growing impact. Currently, building codes and climate policies still focus on operational energy. • Due to upfront carbon emissions representing the greatest share of embodied carbon, the "carbon spike" delays the climate benefits of high-performance or net-zero buildings and makes it harder to meet short-term goals like the Paris Agreement's 2030 emission reduction and 2050 net-zero goals. • Lack of standardization across LCA data and methods hinder comparability among studies and projects. • Emergence of material innovations are not enough until there is a change in the system. Decarbonization of the built environment will require coordination of supply chain, policy alignment, and adoption of circular economy principles. • Implementation of circularity principles in construction are gaining traction.

3.3 Overview of Material Circularity

For Material Circularity, Table 6 was created to present key highlights organized by the thematic categories: **foundational theories and concepts** and **concrete circularity.** Each theme serves to capture major insights that inform current understanding and future direction in addressing circularity within material production and construction.

Table 6 – Summary of Material Circularity Research by Theme

Foundational Theories and Concepts
Description: Articles grouped and reviewed under this category provide core concepts of circularity and their effect on building embodied carbon.
Key Ideas: • Metrics like the Material Circularity Indicator (MCI) and the Building Circularity Indicator (BCI) assess how well materials are sourced, maintained, reused, and recovered. • Design for disassembly (DfD) and adaptability are key enablers of reuse, component recovery, and reduction of end-of-life emissions. • Circularity takes into account how long and how well a product functions throughout its life. Mass-based metrics do not capture the full essence of circularity. Qualitative design attributes must be weighed alongside quantitative data.

Table 2 continued

Concrete Circularity
Description: Articles grouped and reviewed under this category summarize strategies for increasing circularity within concrete.
Key Ideas: • Supplementary Cementitious materials (SCMs) offer a practical path toward circularity, repurposing industrial by-products. • Recycled Concrete Aggregates (RCA) can support circular material flows; however, embodied carbon reductions are modest or insignificant. • Concrete circularity is heavily dependent on structural design and performance. There's a trade-off between these two principles. • Passive sequestration in concrete may contribute to lower net emissions over time.

CHAPTER 4. METHODOLOGY

As outlined in section 2.7 Purpose and Scope of Thesis, this paper seeks to answer three key questions:

1. What percentage of total embodied carbon in construction projects is attributed to concrete, and how does this vary across different project types and locations?
2. How does the incorporation of recycled concrete aggregate (RCA) influence embodied carbon calculations?
3. How can circularity metrics, such as material reuse and recycling potential at the end of life, be incorporated into embodied carbon assessments of concrete?

To address each of these, three complementary methodologies were conducted: an industry data analysis, recycled concrete circularity select literature review, and the application of a Material Circularity Indicator (MCI) on industry data. This section outlines how each of these was performed. Before doing so, it provides context on the source of the industry data and the partnership established to support this research.

4.1 Industry Data

4.1.1 Theory versus Practice

Theoretical concepts provide a starting point for understanding complex subjects, providing the foundation for knowledge development and academic research. However, theoretical models can sometimes be too idealistic, failing to capture the complications and constraints that rule real-world applications. In the field of construction, collaboration between industry and academia is often limited (Shapira & Rosenfeld, 2011), which leads to gaps in understanding the interconnections between theory and real-world applications. The disconnect can impact accuracy and pertinence of studies, as theoretical models may not fully align or be feasible with industry practices.

The construction industry is highly human-driven, making it susceptible to human error, variability in execution, and unexpected challenges. Unlike controlled research environments, construction projects are influenced by external factors, such as weather conditions, supply chain disruptions, regulatory changes, and even politics, all of which can impact project execution and results (Shapira & Rosenfeld, 2011). Moreover, real-world construction operates under constraints that theoretical models may not fully capture. Project budgets, schedules, and client requirements often take precedence over novel innovative and sustainable practices. While these approaches could complement each other, the industry frequently favors traditional, well-established methods due to their reliability and predictability. These types of factors can lead to compromises in the field which may differ from idealized research scenarios.

Another significant challenge academia may face in the subject of construction is its reliance on industry data, which may be limited by the willingness and transparency private companies have when sharing proprietary information. Without access to real-

world data or consultation from industry professionals, research may be at a disadvantage of yielding findings based on assumptions that do not reflect industry conditions.

Therefore, incorporating industry data into research is essential to ensure construction research reflects real-world applications. In terms of embodied carbon assessments and circularity, industry data and insights are invaluable. It can reflect actual estimating methods, procurement strategies, construction methods, and material handling. Additionally, industry data can provide insight into industry trends, including the adoption of new materials and technologies, evolving regulations, and shifting of client priorities.

By partnering up with industry, this research utilizes real-world data to bridge the gap between academic theory and industry practice, offering a more holistic analysis of embodied carbon in construction projects.

4.1.2 General Contractor Partnership

The general contractor providing the industry data for this research is one of the largest builders in the United States, recognized as a leader across various major commercial market segments in the building sector. Known for delivering large and complex projects, this contractor is at the forefront of innovation and sustainability in the industry. Their public commitment to reduce their environmental impact has driven the development of various sustainability initiatives in the following focus areas: embodied carbon, jobsite carbon and water, waste and circularity, building energy and net zero, green building certifications, resilience, and biodiversity protection. As one of the largest general

contractors in the industry, they recognize their influence over building practices and offer services to help clients implement sustainable strategies. Leveraging their extensive network and research initiatives, they can provide guidance tailored to client's priorities, whether in early design decisions, such as mechanical plumbing systems and material selection, or construction-phase sustainability efforts, such as electrifying equipment, waste diversion, and recycling of hard-to-recycle materials.

A key component of their embodied carbon program is the implementation of preconstruction embodied carbon models for all projects exceeding a specific volume threshold ($20M). These models enable early-stage analysis of embodied carbon impacts, allowing for data-driven decision-making as well as industry benchmarking. The contractor is further advancing this initiative by developing as-built models to compare preconstruction estimates with actual material procurement and quantities after a project is complete. Within this program, the contractor also actively assists clients and design partners in identifying and implementing low-carbon material solutions and mitigating embodied carbon emissions.

Beyond embodied carbon, this contractor also commits to the effort of quantifying construction activity emissions (A4–A5 of Figure 1) through their jobsite tracking program. Launched as a pilot in 2019, the program initially enrolled a limited number of projects. Nonetheless, the data collected in this period provided valuable insights into electricity and water consumption patterns and peak usage times across sites. These findings led to the identification of effective reduction strategies, such as LED lighting standards for all temporary lighting, solar-powered light towers, equipment electrification, and optimized fuel use through prevention of equipment idling and the use of diesel and

other biofuels. Notably, A4-A5 emissions extend beyond direct construction activities to include supporting spaces such as construction trailers. The jobsite tracking program includes the tracking of both water and electricity for supporting facilities as well. Personnel working in these temporary facilities are also educated on reducing their operational carbon footprint, further enhancing the impact's program.

Unfortunately, while both aforementioned programs are closely related under the overarching umbrella of embodied carbon, they have not been integrated. Therefore, for the purposes of this research, the dataset obtained from this general contractor exclusively focuses on embodied carbon models developed during preconstruction, excluding operation emissions from construction activities.

4.1.3 Industry Embodied Carbon Models

The dataset utilized in this study was obtained from the industry partner introduced in the previous subsection. As discussed, as part of their sustainability initiatives, this general contractor collected embodied carbon data from over 130 North American commercial construction projects between 2022 and 2024. The total dataset comprises three annual collections, with each successive year expanding scope and project participation. From 2022 to 2024, the numbers of projects included in the data collection grew from 32 to 66, with no project repeated across different years. While all three datasets provide valuable insight, this study focuses on the most recent dataset (year 2024) for analysis.

4.1.3.1 Data Source

The data collected in these datasets originates from the general contractor's internal carbon quantification efforts, which involve requesting individual regionalized offices, or profit centers, to select eligible projects for reporting. To visualize the breadth and distribution across North America, Figure 2 shows the locations of all projects included in the 2024 dataset.

Figure 2 – Map of Project Locations in the 2024 Embodied Carbon Dataset

In order to make reporting manageable, the initial 2022 program focused on two primary construction materials: concrete and steel. The following two years, the material scope was expanded to include asphalt, glass, and wood. For the purposes of this research, the following assumptions were made for each of these materials:

- **Concrete:** Concrete material includes ready-mixed concrete, precast concrete, concrete masonry units (CMU), concrete reinforcement (rebar, wire mesh, and pre- or post-tensioning tendons), aggregates, shotcrete, flowable full, concrete paving, cementitious soil treatment. As a general rule of thumb, components categorized under Construction Specification Institute (CSI)'s MasterFormat Division 03 were considered to be part of the concrete scope.
- **Steel:** Steel is defined as hot-rolled sections, metal decks, plate steels, hollow sections, and merchant bars. As a general rule of thumb, components categorized under CSI's MasterFormat Division 05 were considered to be part of the steel scope. Metal steel doors also fell into this category.
- **Asphalt:** In this study, only asphalt paving materials were included in estimates. As a general rule of thumb, components categorized under CSI's MasterFormat Division 32 were considered to be part of the asphalt scope.
- **Glass:** Glass is defined as flat or processed glass planes used in the exterior building façade and interior storefront applications. Mirrors and door lites were largely excluded.
- **Wood:** Wood is defined as prefabricated mass timber elements, dimensional lumber, and sheet products with defined quantities, such as wood floors and doors). Some miscellaneous wood blocking was included in estimates.

Moreover, selected projects had to meet the following criteria to be reported:

- Project scope had been awarded to contractor or a Joint Venture (JV) led by the contractor.
- Project must either be a ground-up/new construction or renovation/expansion.
- Project scope must include at least three of the five materials tracked.
- Project is in preconstruction at the time of the selection.

In general, preconstruction professionals, who routinely perform internal quantity take-offs for pricing and procurement validation, were responsible for completing the embodied carbon estimate datasets. These individuals were instructed to categorize their projects by building type to the best of their ability and knowledge, selecting from the predefined EC3 categories that included the following:

- **Educational:** Facilities designed for instruction, including schools, colleges, and universities.
- **Industrial:** Buildings dedicated to manufacturing, warehousing, distribution, or other heavy-duty production activities.
- **Institutional - Healthcare:** Facilities providing medical care, including hospitals, clinics, medical offices, care centers, and other health-related services.
- **Laboratory:** Buildings specifically designed for scientific research, experimentation, testing, or analysis.

- **Lodging:** Structures providing short-term accommodations, such as hotels and resorts.
- **Office:** Buildings primarily intended for conducting business, administrative tasks, and professional services.
- **Parking:** Structures built specifically for vehicle storage, such as parking garages.
- **Public Assembly:** Facilities designed for large social gatherings, events, and entertainment, such as theaters, convention centers, arenas, and stadiums.
- **Residential multi-unit:** Buildings intended for long-term housing, comprising of multiple separate dwellings, such as large apartment towers.
- **Data Center:** Facilities designed to house and operate computer servers and data storage systems.
- **Other:** Buildings that do not clearly fit into the categories listed above, are a mix of multiple categories, or have unique, specialized functions

4.1.3.2 Data Collection Methodology

The collection methodology of this industry dataset followed a standardized approach and utilized Building Transparency's EC3 software tool for the full A1-A3 embodied carbon calculations.

First, preconstruction staff created projects in EC3. Creation of these project files included inputting various project details, including project name, client, location, building use type and market segment, square footage, height, and number of stories above and below grade. Next, utilizing the material quantity take-off already performed during preconstruction estimates, preconstruction team members built the embodied carbon model

for each building component within EC3. To do this, material EPDs were chosen from the database and quantity take-offs were entered for each building component—such as foundations and columns. The EC3 software supports various types of units, since they are automatically converted to the necessary equivalent unit for final calculations.

Finally, embodied carbon calculations were determined by the software by multiplying material quantity by its embodied carbon density factor, based on the selected EPDs. These calculations represent the Global Warming Potential (GWP) of materials, expressed in units of kilograms of carbon dioxide (CO_2) equivalents ($kgCO_2e$), which is the standard metric for reporting embodied carbon. EC3 automatically converts materials units as needed to ensure consistency in GWP calculations.

The EC3 software provides four types of embodied carbon values based on various EC3 benchmarks: Reference Embodied Carbon (EC), Conservative EC, Achievable EC, and Realized EC. These benchmarks are based on the ranges provided in the industry-wide and manufacturer-specific EPDs. Because EPDs must report embodied carbon as ranges, these benchmarks allow for a full understanding of their potential variability: conservative EC reflects the upper bound (worst-case scenario), while the Achievable EC reflects the lower bound (best-case scenario). By default, the Conservative EC is used as the Realized EC of the material.

4.1.3.3 Methodology Limitations

Despite efforts to standardize the collection of this study's dataset, several limitations emerged. First, there was assumed variability in take-off methods for each project. Even though estimating methods are intended to be standardized across the source company, take-offs were still conducted individually and, therefore, allowed for variation in execution. Second, accuracy of embodied carbon calculations stemmed from the accuracy of EPD selection. For this data collection, EPD selection relied on user knowledge, which was assumed to not yet be widespread within preconstruction teams. Finally, the construction projects of this study differed in level of design. For instance, exact concrete mixes and manufacturers are often undetermined during preconstruction. Therefore, industry-wide EPDs were predominantly selected throughout these datasets, which was assumed to lead to broader embodied carbon ranges overall. As a result, the dataset's embodied carbon estimates tend to be conservative, with models defaulting to Conservative EC benchmarks as stated in the previous subsection.

4.2 Industry Data Analysis

The outlines the methodology used to synthesize and analyze the embodied carbon industry following subsections data obtained from the general contractor partner. As previously mentioned, the dataset used in this research is from 2024 and contains 66 construction projects total. The dataset was collected and housed in EC3. In order to help address the research questions of this thesis, the data was extracted, aggregated into one list, classified regionally, and summated for individual material embodied carbon and project totals.

4.2.1 Data Processing

Before turning over to the research team, all project data was anonymized by the general contractor. Project names, client information, and any other specifically descriptive characteristics were removed, and names were replaced by a combination of words and numbers. Examples of names were "Peru Goshawk 4" and "Maroon Woodpecker 52." Since the dataset was housed in EC3, project data had to be extracted from the software individually to be manipulated and analyzed. This process involved downloading spreadsheets for each project containing component-level quantity take-offs and corresponding embodied carbon estimates across the different benchmark levels.

To enable a comprehensive analysis of the full dataset, individual project data from the 66 projects was consolidated into a single master spreadsheet. This process included:

1. Listing all projects and compiling relevant project details into a single list. Details included were anonymized name, shortened name form (i.e. PG4 for Peru Goshawk 4), location, building use designation, area (sq ft), number of stories, height, and level of document development (i.e. concept, schematic, detailed, and construction documents).
2. Categorizing projects into one of five US regions (Northeast, Southeast, Midwest, Southwest, West) or Canada, based on the location.
3. Extracting total embodied carbon estimates for each of the embodied carbon benchmarks (i.e. Reference EC, Conservative EC, Realized EC, and Achievable EC) per project.

4. Calculating embodied carbon area densities for each of the benchmarks by dividing step 3 values by the designated total project area.
5. Aggregating embodied carbon estimates per material (concrete, steel, asphalt, glass, and wood). Since individual project data summarized their reported embodied carbon by elements and building components, these values were summed for each material to determine the total embodied carbon contribution for each material. Additionally, material embodied carbon breakouts were only completed on the Conservative/Realized EC benchmark values.

By completing these steps, the master data was able to provide all the critical information for data analysis in one place.

4.2.2 Data Analysis Approach

To effectively interpret and visualize the synthesized industry embodied carbon data, both tabular and graphical analysis methods were employed in this research. This type of organization and visual representation allowed the researcher to compare variables, identify patterns, and summarize findings efficiently.

As discussed in the previous section, all project data was compiled into a master spreadsheet and categorized by geographic region and building type. Organizing the data in this tabular format enabled direct comparisons between projects and provided a structure foundation for further analysis. Utilizing this compiled data, various tables were generated

to present key project details and their corresponding embodied carbon estimates. The dataset was segmented by region, building type, and material, to evaluate trends in embodied carbon performance across these different factors. Depending on the data assessed, embodied carbon area density was calculated in order to normalize the comparison across projects. Then, charts and graphs were used to illustrate these variations.

By structuring the dataset in this manner, the data analysis provided insight into embodied carbon trends across a diverse set of real-world construction projects and factors.

4.3 Recycled Concrete Circularity Select Literature Review

To examine how the use of RCA in concrete influences embodied carbon calculations, a select literature review was conducted. This review focused on existing studies that quantify the impact of RCAs on concrete embodied carbon. The goal was to synthesize key findings regarding the extent to which aggregates contribute to total embodied carbon.

A search for relevant literature was conducted using Google Scholar, with the keywords “recycled concrete aggregate” and “embodied carbon” used together to refine the results. From the search, nine papers were selected based on their content relevance to RCA’s impact on concrete embodied carbon calculations. These previous studies assessed how RCAs compare to virgin aggregates in terms of carbon intensity, energy consumption, and potential emission reductions. Additionally, it was important for the selected literature

to address the trade-offs associated with using RCAs, such as its impact on the strength and lifespan of concrete.

By summarizing existing literature, this analysis provided a foundation for understanding RCAs and their role in reducing embodied carbon in buildings, while also qualitatively assessing the feasibility of widespread adoption of circular practices in concrete production.

4.4 Material Circularity Indicator

This research incorporated the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation to complement the embodied carbon assessments and explicitly assess material circularity. It quantitatively measured how well a product performs in the context of a circular economy. MCI scores range from 0 to 1, with higher values indicating greater circularity. The MCI assessed circularity based on three product characteristics: the portion of virgin material used versus recycled or reused content, the portion of material that becomes unrecoverable waste at the end-of-life, and the utility factor that accounts for the lifespan and functional efficiency of the product (Goddin et al., 2019).

The MCI was selected for this research due to its growing application within the built environment (Goddin et al., 2019)(Amarasinghe et al., 2024) (Dräger et al., 2022) (Cottafava & Ritzen, 2021) (Peña et al., 2021). Recent studies have applied MCI to evaluate construction products and materials, further validating its relevance in this sector.

For example, Dräger et al. (2022) adapted this indicator to assess the circularity of 89 building products listed in a German environmental database, highlighting its potential for product-level circularity analysis in the construction industry. Similarly, Amaransighe et al. (2024) included the MCI in the development of their material circularity evaluation framework for building construction projects.

In the MCI formulation, the amount of Virgin Material V for a product p, expressed as $V_p = M_p(1 - F_{r,p} - f_{u,p})$, is equal to the total mass of the product M_p times the fraction of the material that is neither reused $F_{u,p}$ or recycled material $F_{r,p}$. The Product Utility X_p, expressed as $X_p = \left(\frac{L_p}{L_{av,p}}\right)\left(\frac{U_p}{U_{av,p}}\right)$, is calculated by multiplying the lifetime ratio $\left(\frac{L_p}{L_{av,p}}\right)$, which is the product lifespan L_p over the average lifetime of the products in the market $L_{av,p}$, by the intensity ratio $\left(\frac{U_p}{U_{av,p}}\right)$, which is the intensity of use per year U_p over the average market intensity of use $U_{av,p}$.

Due to lack of data, all product utilities were set to equal 1. This assumed that each material is used for its full expected lifetime, without premature replacement or failure. The amount of unrecoverable waste Wp, expressed as $W_p = W_{0,p} + W_{F,j}$, was computed by adding the total amount of waste directed straight to the landfill $W_{0,p}$ and the waste generated during the recovery process $W_{F,p}$. This combination ensured that unrecoverable waste captured both initial disposal and additional losses that arose from the process of recycling or recovery, since most recovery methods are not completely efficient. For the purposes of this research, $W_{F,p}$ was assumed to equal 0, meaning the recovery process is 100% efficient (Cottafava & Ritzen, 2021).

Utilizing the factors and assumptions above, the Linear Flow Index (LFI) is calculated as shown in Equation 1. The LFI measures the proportion of a material's linear flow through a system, starting from virgin materials and ultimately becoming unrecoverable waste. The resulting index ranges between 0 and 1, where 0 represents a fully circular flow with no waste generation and 1 indicates a fully linear process where all material becomes waste and there is no diversion from landfill. For 100% efficient recovery processes, the LFI was calculated as follows:

$$LFI_p = \frac{(V_p + W_p)}{2M_p} \quad (1)$$

The MCI of a product was defined by considering the LFI of the product and a factor *F(X),* where *F* is a function of the utility *X* that determines the influence of the product's utility on its MCI. Equation 2 below was used to calculate MCI of a product.

$$MCI = 1 - LFI \cdot F(X) \quad (2)$$

To account for the product utility relative to industry averages, the MCI was adjusted by a utility factor of $F(X) = \frac{0.9}{x}$. This factor ensured that products with shorter

lifespans and lower utilization rates received lower circularity scores (i.e. conservative measuring). The 0.9 constant was chosen to align with the MCI scale convention, which ensures that fully linear products (LFI = 1) result in an MCI score of 0.1 (Goddin et al., 2019).

The analysis for this section involved calculating the MCI for each of the five materials included in the industry dataset—concrete, steel, asphalt, glass, and wood—based on their respective standard characteristic and end-of-life scenarios. Sources for these industry values include: ("When a Building Is Demolished, How Are Materials Recycled?," n.d.), (*» Recycled Asphalt Mixes*, n.d.), (Williams & J. Richard Willis, 2020), (*Recycled Content in Concrete*, n.d.), and (Carton, 2024). This approach provided a standardized method to directly compare the circularity potential of these different materials at their standard industry use, facilitating the comparison of their relative circularity performance in relation to the other materials.

Subsequently, a focused analysis was conducted on concrete, where the MCI was calculated at varying levels of recycled content (20%, 30%, 40%, and 50%) as well as varying levels of end-of-life recyclability (60%, 70%, 80%, 90%, and 100%) to assess how incremental increases in these two dimensions influence circularity. By increasingly adjusting the recycled content in concrete, the research explored the relationship between recycled aggregates in concrete and its circularity potential, which then was integrated with accompanying embodied carbon assessments. By increasingly adjusting the recyclability of concrete at the end-of-life, this research effort explores the relationship between concrete's secondary uses and its circularity potential, which was integrated with accompanying embodied carbon assessments. Together, this approach enabled

comparisons between higher levels of recycled concrete and other materials, providing insights into the effectiveness and practical value of increasing recycled content and recyclability at the end-of-life as a circularity strategy.

CHAPTER 5. RESULTS

This section presents the findings from the analyses conducted according to the three methodologies outlined in the last section: an industry data analysis, the select literature review on RCA impacts on embodied carbon, and the evaluation of circularity metrics (MCI) in concrete. Each of the following subsections summarize the outcomes, highlight key patterns, and provide insights that address each of the research questions guiding this study.

5.1 Industry Data Analysis: Embodied Carbon Trends Across Projects

The industry dataset obtained and analyzed in this study consisted of the preconstruction embodied carbon estimates of 66 North American construction projects, categorized by geographic regions and building types. Through tabular and graphical analysis, the data reveals distinctions in embodied carbon distribution across materials, regions, and building types.

Firstly, as expected and illustrated in Figure 3, concrete was cumulatively the largest contributor to embodied carbon emissions across the 66 analyzed projects, representing approximately 56% of total embodied carbon. Steel followed as the second largest contributor at 33%, with significantly smaller contributions from asphalt, glass, and wood.

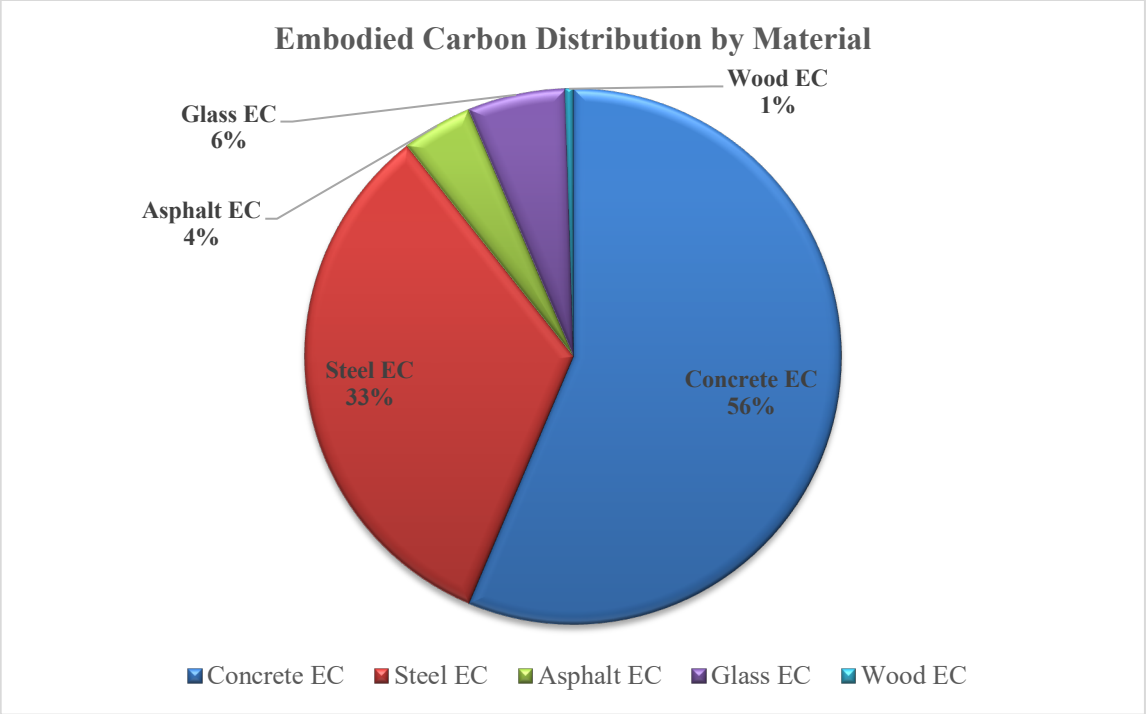

Figure 3 – Embodied Carbon Distribution by Material

Next, regional analysis of material embodied data distribution, as portrayed in Figure 4, demonstrates notable variations in embodied carbon area densities. Embodied carbon area densities, measured in $kgCO_2e$ per square foot, represents the amount of carbon associated with the materials used in a building normalized by its floor area. This approach allowed for comparisons across projects of varying sizes. Markedly, projects in the Northeast and Southeast show higher embodied carbon intensities compared to those in the Midwest and Southwest. Furthermore, embodied carbon intensity of concrete is consistently lower in projects located in the West and Midwest than those in the Northeast and Southeast.

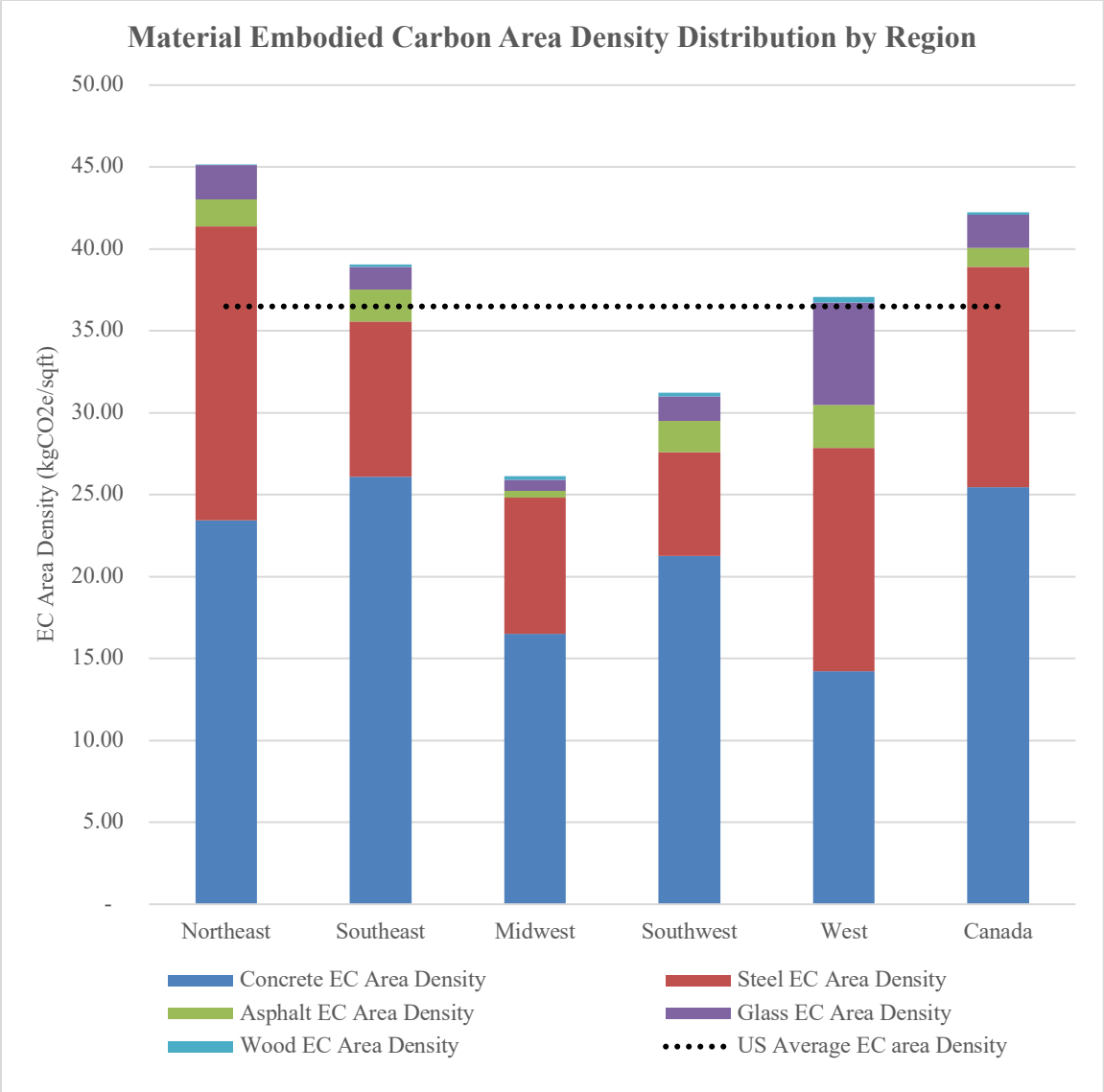

Figure 4 – Material Embodied Carbon Area Density Distribution by Region

It was also essential to review how building use affected embodied carbon estimates. Figure 5 shows the distribution of embodied carbon area densities for all five materials across the different building types. Significant variability is observed across different building types, with public assembly and industrial facilities demonstrating notably higher embodied carbon area densities overall. Similarly to the regional

distribution, projects with the highest embodied carbon area density also corresponded to the accompanying higher carbon intensities of concrete as well.

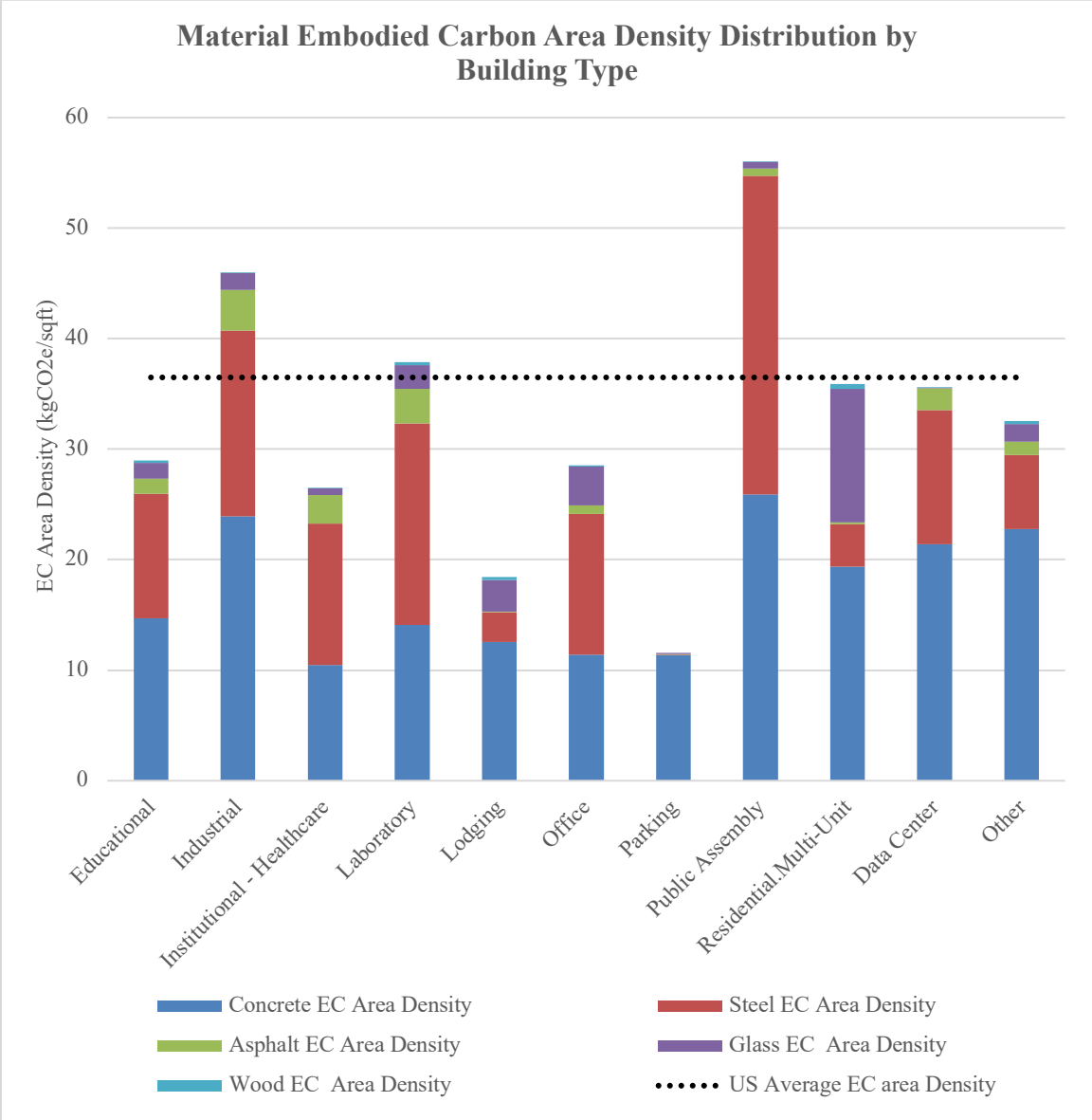

Figure 5 – Material Embodied Carbon Area Density Distribution by Building Type

To further validate the observed regional differences in embodied carbon estimates as well as the variations in embodied carbon per building type, it is important to consider how the dataset building types vary by region. Different building use categories will inherently have distinct material profiles and accompanying embodied carbon make-ups. Moreover, a regional analysis could yield misleading conclusions if the projects representing each region lack diversity in building types. Table 7 outlines the distribution of project building types by region to help bolster data clarity.

Table 7 – Distribution of Project Building Types by Region

	Region						
Building Type	***Northeast***	***Southeast***	***Midwest***	***Southwest***	***West***	***Canada***	***Total***
Educational	2	2	0	0	1	1	**6**
Industrial	2	1	1	0	1	0	**5**
Institutional - Healthcare	2	0	2	0	1	1	**6**
Laboratory	1	2	0	0	0	0	**3**
Lodging	0	0	0	2	0	0	**2**
Office	1	0	1	1	0	0	**3**
Parking	0	0	1	0	0	0	**1**
Public Assembly	2	0	0	1	0	0	**3**
Residential.Multi-Unit	1	1	1	0	2	0	**5**
Data Center	1	4	3	1	0	1	**10**
Other	2	5	7	3	5	0	**22**
TOTAL	**14**	**15**	**16**	**8**	**10**	**3**	**66**

Focusing on the embodied carbon area density of one building type across regions offers valuable insight for how geographic regions may affect embodied carbon. Since data centers were the most represented type of project, besides "other," across all regions, these were selected for further analysis. Table 8 summarizes the variations in embodied carbon area densities between regions. Notably, the Southeast shows the largest carbon footprint for data centers, while the Midwest shows the least. The West region was disregarded due to lack of data center projects in the region.

Table 8 – Data Centers Embodied Carbon Area Density Per Region

	Northeast	***Southeast***	***Midwest***	***Southwest***	***Canada***
Data Center EC Area Density	39.34	48.28	27.50	35.30	31.96

5.2 Recycled Concrete Circularity and Carbon Reduction

To explore how recycled concrete aggregate (RCA) influences embodied carbon calculations in concrete, this subsection reviews nine articles that quantified the environmental and material performance of RCA in new concrete mixes and examine various strategies for achieving low-carbon concrete. These previous studies reviewed include laboratory experiments, real-world case studies, LCAs, and analyses of EPDs. Collectively, the select literature review revealed that while RCA use is widely recognized to contribute towards circularity and resource efficiency, its direct influence on embodied

carbon is more nuanced and situational. Appendix C lists the nine studies reviewed in more detail. A synthesized discussion of their collective insights follows now.

5.2.1 Recycled Concrete and Its Uses

RCA refers to crushed material derived from previously hardened concrete, typically sourced from C&D waste. It is most commonly produced by breaking up end-of-life concrete elements—such as slabs, beams and columns from buildings and infrastructure—and processing them through crushing, screening, and removal of contaminants. Once processing is complete, RCA can be reused as a partial or full substitute for natural aggregate (NA) in new concrete mixes.

The use of RCA represents a key strategy in advancing the circularity of concrete construction. In a traditional linear system, concrete would be demolished and sent to a landfill. In contrast, reusing and recycling concrete helps to close the material loop by reintroducing waste into the production cycle. This reduces the demand for virgin materials, lowers the volume of landfill waste, and supports resource efficiency in line with circular economy goals.

RCA is most often used in non-structural applications such as road base, backfill, or pavement layers, where lower mechanical demands make it a straightforward replacement for NA. In fact, a study published by the EPA in 2018 reported that approximately 82.4% of concrete C&D waste was diverted from landfills and directed toward next-use applications (*Advancing Sustainable Materials Management: 2018 Fact*

Sheet, n.d.). Of this recovered material, about 90% was reused as aggregate, primarily for base layers and fill, while the remaining 10% was incorporated into manufactured products (*Advancing Sustainable Materials Management: 2018 Fact Sheet*, n.d.).

Nonetheless, research and case studies have demonstrated that with careful mix design and quality control, RCA can also be incorporated into structural concrete. In this application, RCA is generally used as partial replacement, commonly between 20-50%, to balance environmental benefits with strength and durability requirement. As the construction industry moves toward decarbonization and sustainable material practices, RCA continues to gain traction as a lower-impact material option that can complement broader strategies for reducing embodied carbon and other environmental impacts in the built environment.

5.2.2 Role of Aggregates in Concrete Properties

Aggregates make up a majority of the total volume of concrete used in the built environment, making up 60 to 75%. They play a critical role in determining the mechanical behaviour, durability, and long-term performance of concrete. The properties of aggregates, such as size, shape, density, porosity, water absorption, and even surface texture, can influence concrete's workability, strength, shrinkage, creep, and permeability. Consequently, the type and quality of aggregate used in concrete mixes can significantly affect the engineering performance of the final product which is why aggregates must be carefully selected and specified based on their physical properties and their intended application. Not all aggregate types are suitable for all concrete uses, hence, the importance

of the engineer's role to ensure that aggregate selection aligns with structural, durability, and performance requirements is key.

RCAs, while possibly similar in size and gradation as NAs, differ substantially in physical characteristics. The presence of the adhered mortar from the original concrete usually results in higher porosity, greater water absorption, and lower density, all of which can negatively affect the mechanical performance of a new concrete mix (McNeil & Kang, 2013). Additionally, due to the residual mortar adhered to its surface, RCA is often characterized as more rounded and spherical in shape compared to NA, where NA is typically more angular with smooth, uncoated sides. In Los Angeles abrasion tests—a standard method for evaluating durability of aggregate material on its own—RCA was shown to generate a higher amount of fine particles than NA (McNeil & Kang, 2013). This is likely because the residual mortar in RCA breaks off more easily during abrasion, whereas NA lacks a comparable weak surface layer to lose (McNeil & Kang, 2013).

This abrasion and breakdown response of RCA have broader implications for how RCA interacts with the cement paste in new concrete. The interfacial transition zone (ITZ) between RCA particles and the new cementitious matrix is inherently weaker than in mixes with natural aggregate, in part because the residual mortar prevents strong bonding with the new paste and introduces more porous, brittle regions that can become points of failure (McNeil & Kang, 2013). Several studies—including those by McNeil & Kang (2013), Xiao et al. (2018), and Shi et al. (2016)—highlight how these characteristics contribute to a reduced modulus of elasticity, increased deflections, reduced compressive strength, and smaller crack spacing, and larger crack widths in RCA concrete.

Notably, Shi et al. (2016) takes this step further by exploring treatment methods to mitigate the negative effects of residual mortar—such as through carbonation, polymer impregnation, and chemical surface modification. These approaches aim to strengthen or densify the ITZ, ultimately improving the structural performance of RCA concrete and making it a more viable alternative in higher-performance applications.

Despite these limitations, many experimental studies show that concrete mixes with partial RCA replacement, typically up to 30%, can achieve comparable compressive and tensile strength to conventional mixes. For instance, López Ruiz et al. (2022) evaluated several recycled concrete mixes in Spain and found that 20-30% RCA replacement in structural concrete maintained acceptable performance. Meanwhile, 100% RCA was viable in non-structural applications and delivered other notable environmental and economic benefits. In a separate study, Xiao et al. (2018) conducted a full-scale high-rise case study and confirmed that RCA concrete was observed to develop greater mid-span deflections and slightly wider crack during beam testing. However, these still performed within acceptable code limits in the city of Shanghai, China. These findings suggest that, when used meticulously, RCA can provide acceptable performance in both non-structural and selected structural contexts, especially when paired with optimized mix designs and quality control practices.

5.2.3 Environmental Impact of RCA Use

Beyond performance considerations, the use of RCA plays an important role in reducing the environmental footprint of the construction industry. Concrete production

consumes vast quantities of raw material, particularly natural coarse and fine aggregates, which are finite resources under an increasing global demand for urbanization (Kadawo et al., 2023). The construction industry is the largest consumer of aggregates worldwide, using them in concrete, asphalt, road base, drainage, erosion control, and more (*What Are Aggregates and How Are They Used?*, n.d.). In regions experiencing rapid urban development, this over extension of sand and gravel can lead to pressures on natural resources, ecosystem disruptions, erosion, and biodiversity loss, making it crucial to explore alternative materials such as RCA (*Sand Mining*, 2023).

In addition to resource depletion, the disposal of concrete waste into landfills contributes to broader environmental degradation. As mentioned in the background, landfills not only occupy valuable land, but they also pose risks of soil and groundwater pollution, increased GHG emissions, and long-term management challenges. Diverting concrete waste from landfills through RCA production supports circular economy principles and reduces the overall volume of waste led into landfills (*Advancing Sustainable Materials Management: 2018 Fact Sheet*, n.d.).

While the use of RCA can contribute to meaningful reductions in environmental impact categories, it does not automatically translate to substantial decreases in embodied carbon. In fact, several studies have shown that global warming potential (GWP) reductions associated with RCA use tend to be modest (Kadawo et al., 2023). For example, Kadawo et al (2023) found that replacing NA with RCA led to only 2-10% reduction in GWP even in concrete mixes with full aggregate substitutions. This conclusion aligns with understanding the broader industry data for concrete. That is, although aggregates make up 60-75% of concrete by volume, their embodied carbon contribution is relatively small. In

most mix designs, cement accounts for more than 80-90% of total GWP, while aggregates contribute only a fraction of that—typically in the range of 2-10% (Kadawo et al., 2023). As a result, changes to aggregate sourcing and type may only have limited impact on overall embodied carbon, unless they are coupled with reductions in cement content or the use of alternative binders.

Nevertheless, embodied carbon is not the only dimension in the grand scheme of environmental impacts. While RCA may offer limited reductions in GWP, it performs notably better in other equally important environmental categories, improving overall sustainability outcomes. In particular, López Ruiz et al. (2022) demonstrated that RCA use in concrete led to significant reductions in resource depletion, ozone layer depletion, and acidification potential when compared to conventional concrete. These benefits highlight the broader environmental value of recycling concrete not just in carbon savings, but also for reducing the overall ecological footprint of material production and waste management.

5.2.4 Transportation and Recycling Logistics

The environmental benefits of using RCA are not solely determined by the material itself, but they are highly influenced by transportation and processing logistics. In fact, distance matters just as much as material composition when calculating the embodied carbon of concrete. This was highlighted in the Wijayasundara et al. (2017) study, which found that transportation distances significantly affect the total environmental impact of RCA, especially when upstream processes and aggregate sourcing are included in the LCA.

In LCAs of concrete, the A1-A5 system of Figure 1 boundary would capture emissions from raw material extraction through concrete placement and installation. Of these stages, A2 (transport of raw materials to the concrete plant) and A4 (transport of fresh concrete to the jobsite) are particularly sensitive to the distance materials must travel. NAs, such as sand and gravel, are frequently sourced from quarries located far from urban centers, where land availability and geological conditions allow for the large-scale extraction, increasing the emissions associated with transport.

RCA, on the other hand, introduces an alternative sourcing path. Rather than being extracted from a quarry, RCA is typically produced by processing demolished concrete from buildings or infrastructure at the end of their service life (Alberto López Ruiz et al., 2022). The dismantled material is first transported from the demolition site to a recycling facility, where it is processed into usable aggregate. From there, the recycled aggregate is sent to a concrete batching plant to be incorporated into a new mix. Finally, the RCA concrete is delivered to the jobsite for placement.

Because of the extended transportation chain, the environmental benefits of RCA are highly sensitive to proximity. To achieve positive or net-zero carbon savings, RCA must be sourced, processed, and utilized close to the final point of use for longer haul distances can quickly offset the benefits of avoiding virgin aggregate extraction. A key advantage of RCA lies in the fact that demolished structures are typically located in or near urban centers, where construction demand is also concentrated.

When recycling facilities are situated within or close to these urban areas, the total distance traveled from demolition to reuse can be minimized, enhancing the carbon

efficiency of RCA concrete. López Ruiz et al. (2022) clearly demonstrates this trade-off by comparing a range of structural and non-structural concrete mixes using different RCA replacement ratios and two recycling scenarios: off-site and on-site processing. In the off-site scenario, demolition waste was transported to an external recycling facility, where it was processed into RCA before being sent to a concrete plant. In the on-site scenario, a mobile crushing and screening plant was used at the demolition site to produce RCA locally, which was then transported to a nearby concrete plant for mixing. This previous study presented that on-site recycling consistently outperformed off-site recycling in the terms of carbon emission. By eliminating one leg of material transport, the on-site scenario minimized transport-related emissions and reduced total embodied carbon.

This insight is echoed in the works of Novakova et al. (2023) and Kadawo et al. (2023), both of which underscore the critical role transportation distances play in determining total carbon savings of RCA concrete. Both studies concluded that meaningful carbon savings are only realized when transport distances are minimized, reinforcing the need for regional sourcing and transportation efficiency in low-carbon concrete design strategies. Together, these studies highlight how logistical context is essential to unlocking full environmental benefits of RCA.

The use of on-site (mobile) crushers presents a promising solution to this logistical challenge. By eliminating the need for long-distance hauling of both demolition waste and RCA, mobile plants can streamline the circular process, reduce transportation emissions, and achieve greater carbon savings. In contrast, off-site recycling, while still beneficial for diverting waste, can result in additional transportation emissions that may reduce or even negate the GWP advantages of RCA, particularly if recycling facilities are widely

dispersed. As the use of RCA in concrete expands, the industry will need to strive towards the adoption of on-site recycling plants.

5.2.5 Emerging Applications and Extended Carbon Reductions

While most research on recycled concrete focuses on RCA as a substitute for NA, emerging studies are beginning to explore its new potential as a low-carbon cementitious binder. These applications go beyond conventional replacement and consider how recycled concrete waste can contribute to alternative binder development, material circularity, and deeper embodied carbon reductions.

One innovative approach is highlighted by Rodriguez-Morales et al. (2024), where the use of pulverized hardened concrete (PHC)—essentially ground-up demolished concrete—was investigated as a precursor in one-part alkali-activated cements (AACs). This previous research effort demonstrated that PHC, when combined with sodium silicate and portland cement, could produce binders with compressive strength up to 50 MPa while reducing carbon emissions by as much as 51% along with significant reductions in energy demand and cost.

These benefits are not all realized simultaneously. Rodriguez-Morales et al. (2024) also found a clear trade-off between mechanical performance and environmental savings. For instance, utilizing 25% PHC in the binder reduced comprehensive strength from 63.2 MPa (reference concrete) to 50 MPa, while achieving a 31.6% reduction in carbon emissions, no energy savings, and a 20% cost reduction. On the other end of the spectrum,

full substitution of cement by PHC (85% PHC + 15% CSS) resulted in a much lower comprehensive strength of 16 MPa, but achieved dramatic savings of 89.6% in carbon emissions, 57.2% in energy demand, and 79.0% in cost. Nonetheless, this innovative approach not only reuses material content within concrete, but it also contributes to binder-related emissions. These results emphasize the overreaching principle of low-carbon concrete design: whether incorporating recycled concrete as an aggregate or using it as a binder, engineers must carefully weigh structural performance requirements against environmental goals to determine the most effective and context appropriate solution.

Despite advancements like the ones presented by Rodriguez-Morales et al. (2024), one consistent theme across the literature is that RCA use alone is insufficient to deliver substantial carbon reductions, especially when cement content remains high. As shown in multiple studies, including Wijayasundara et al. (2017) and Kadawo et al. (2023), the binder phase remains the dominant contributor to embodied carbon in concrete. Therefore, the most impactful environmental strategies tend to pair RCA use with the incorporation of supplementary cementitious materials (SCMs) such as fly ash, slag, silica fume, or calcined clays. These SCMs can replace portions of cement while maintaining or even enhancing performance, offering a dual pathway to low-carbon concrete (Novakova et al., 2023).

Taken together, these emerging practices reflect a shift toward holistic mix design strategies that address aggregate and binder impacts. They also highlight the potential for recycled concrete to play a more integral role in the development of low-carbon concrete not just as a replacement aggregate, but also as an active component in the cementitious system. Notably, expanding the use of RCA and pairing it with SCMs offer a pathway to

not only reduce embodied carbon, but also enhance material circularity alongside broader environmental benefits, including reductions in ozone depletion, acidification, and resource depletion.

Finally, emerging research has begun exploring innovative uses of recycled concrete beyond aggregate substitution, including its use as a precursor in alternative cementitious binders (Rodriguez-Morales et al., 2024). These applications show promising reductions in carbon emissions, energy use, and cost, however, they involve trade-offs in strength that need to be carefully balanced. A recurring theme across all studies is the importance of pairing RCA use with SCMs to meaningfully reduce GWP while preserving structural performance.

Overall, the body of literature reviewed in this section illustrates that RCA is most effective as part of a holistic strategy, where optimization between material selection, binder innovation, and logistics efficiency collectively deliver measurable carbon reductions, advancement towards circularity, and enhancement in environmental stewardship in the built environment.

5.3 Material Circularity Indicator: Assessing Circularity in Recycled Concrete

This section shows the results of a complementary analysis that was conducted, which aimed to explore how incremental increases in recycled content within concrete mixes and end-of-life recyclability affect its MCI and whether such increases yield enough circularity improvements to justify investments, especially considering the structural and

durability limitations associated with high levels of recycled content. To meet this aim, three separate MCIs analyses were conducted. The first evaluated baseline MCI values for all five major materials included in this study—concrete, steel, asphalt, glass, and wood—using industry-standard assumptions for virgin, recycled, and reused content, as well as end-of-life recovery potential. Table 9 outlines the MCI factors, as well as the calculated MCI values.

Table 9 – MCI Values of Five Common Building Materials

Material	**MCI**	**Virgin content (%)**	**Recycled content (%)**	**Reused content (%)**	**Recyclability (%)**	**Utility**
Steel	0.798	40	60	0	95	1
Asphalt	0.730	55	45	0	95	1
Glass	0.730	50	50	0	90	1
Wood	0.460	90	5	5	70	1
Concrete	0.438	85	15	0	60	1

The material MCI values in Table 9 are presented in decreasing order, with steel displaying the highest circularity value and concrete the lowest. Based on industry-standard assumptions for material composition and end-of-life treatment, concrete demonstrates the

least circularity potential among the materials analyzed. This outcome reflects concrete's current dependence on virgin material and its limited recovery or reuse at the end of life. In most cases, even though concrete is diverted from landfill or repurposed for secondary uses—such as a sub-base for roads—at a rate exceeding 50%, these recovery practices are not sufficient to offset the heavy reliance on virgin material.

The next MCI analysis focused specifically on concrete, calculating MCI values for mixes with varying recycled content in concrete, ranging from 20% to 50%, to determine how circularity changes with increasing substitutions. The industry standard for recyclability was kept constant throughout the analysis. Results are summarized in Table 10.

Table 10 – Concrete MCI Values for Various Recycled Concrete Contents

Concrete Recycled Content	**MCI**
20%	0.460
30%	0.505
40%	0.550
50%	0.595

The comparison displayed in Table 10 was intended to assess whether increasing the recycled content of concrete significantly enhances its circularity potential. As shown, even with increases in recycled content up to 50% – which corresponds to nearly 100% replacement of NA and given that aggregates typically make up 60-75% of concrete's total volume, concrete's MCI values only modestly improved. While it surpassed wood at around 30% recycled content, it never reaches the levels observed for steel and glass. This is particularly noteworthy since, as discussed in the RCA literature review, aggregate replacement in practice is often limited to 20-30%, making this 50% scenario a relatively aggressive benchmark, notwithstanding the other conservative assumptions and calculations herein. The overall results highlight the limitations of concrete in achieving high circularity scores, even when virgin material replacement strategies are implemented.

A final MCI analysis was conducted to evaluate how the circularity potential of concrete would be affected with improved recyclability and landfill diversion. For this assessment, the MCI of concrete was calculated using a range of recyclability rates, ranging from the industry standard of 60% up to 100%. Recycled and reused content was kept a constant at industry standards. The results are presented in Table 11.

Table 11 – Concrete MCI Values for Various Recyclability Efficiencies

Recyclability	MCI
60%	0.438
70%	0.483
80%	0.528
90%	0.573
100%	0.618

Similar to the observations from Table 10 regarding increased recycled content in concrete, improvements in recyclability of concrete also led to higher circularity potential. However, these improvements were relatively modest. MCI values surpassed those of wood at around 70% recyclability, but even at 100%, they did not reach the levels observed for steel and glass. Correspondingly, this trend emphasizes the limitations concrete has in achieving high circularity scores, even when complete diversion of concrete from landfills is achieved.

CHAPTER 6. DISCUSSION

This thesis set out to explore the intersection of embodied carbon and circularity in construction through three key research questions:

1. What percentage of total embodied carbon in construction projects is attributed to concrete, and how does this vary across different project types and locations?
2. How does the incorporation of recycled concrete aggregate (RCA) influence embodied carbon calculations?
3. How can circularity metrics, such as material reuse and recycling potential at the end of life, be incorporated into embodied carbon assessments of concrete?

Each of these questions builds upon the previous one, moving from a broad understanding of industry carbon trends to a deeper evaluation of materials and circularity tools that can guide future reduction strategies, especially regarding decision making of concrete materials.

A core objective of this research was to bridge the gap between theory and practice. While academic studies and LCA models offer critical insights into embodied carbon, they often rely on idealized conditions or theoretical assumptions. In contrast, real-world construction projects are influenced by regional practices, material availability, budget constraints, supply chain variability, and client input. By analyzing a dataset of 66 projects from across North America, this research provides a rare window into how embodied carbon is measured and addressed in practice using the analytical tools of academia.

The next subsections explore how concrete's embodied carbon footprint varies across real projects depending on their characterizations, how RCA is being utilized in practice, and how circularity can be quantified using tools like the MCI. Together, the discussion offers a comprehensive understanding of where low-carbon and sustainable concrete strategies must be directed.

6.1 Interpreting Trends in Industry Data

The industry dataset utilized in this research offers both scalability and specificity that are too often missing from pertinent academic literature (Shapira & Rosenfeld, 2011). Not only does this study's dataset include a broad range of building types and regional designations, but it also captures the modeling approaches and assumptions made by preconstruction professionals during design and estimating phases. By examining this data, research can gain a more accurate picture of the status quo in embodied carbon performance across the industry and can begin identifying where and how significant reductions are most achievable. Thus, this research contributes not only to the academic conversation around decarbonization but also to practical strategies that stakeholders can use to evaluate and reduce embodied carbon in real-world projects.

The analysis conducted on the industry dataset revealed several trends that deepen general understanding of current industry practices. Most notably, concrete consistently emerged as the largest contributors to embodied carbon across projects, accounting for approximately 56% of total material-related emissions in this dataset. While these results are based on material-specific estimates and do not reflect functionally equivalent

comparisons across entire building system, like a WBLCA would, they still provide meaningful insight into where carbon hotspots appear in industry practice. This result reinforces the urgent need to prioritize emission reductions from concrete (e.g., material optimization or low-carbon mix design) given its substantial contribution to embodied carbon in the built environment.

Moreover, the data also showed clear trends in embodied carbon intensity based on both region and building type. Among the building uses analyzed, data centers and industrial facilities exhibited some of the highest embodied carbon per square foot. These results may likely be linked to the structural demands and high material volumes associated with these project types, which often have large footprints and limited architectural detail. In general, data centers and industrial buildings tend to require highly enclosed building envelopes, often with minimal glazing and extensive use of concrete walls, to meet thermal control, security, and operational requirements, and safety standards.

On the regional level, projects located in the Northeast and Southeast were found to have higher embodied carbon densities than those in the Midwest and West. While several factors may contribute to this pattern, potential causes include material sourcing logistics, regional code requirements, climate adaptations, and differences in construction practices. For example, the Northeast's higher embodied carbon intensities could be attributed to a combination of factors: buildings in this region may be designed with heavier envelopes to meet energy performance standards and withstand colder climates; architectural strategies that prioritize daylighting could lead to greater use of high-carbon materials like glass and steel; and denser urban settings could require the need for more vertical complexity that require carbon-intensive materials given urban space limitations.

Also, longer transportation distances during the concrete material production stage, due to factors such as limited local manufacturing, may further elevate embodied carbon values in this region.

Additionally, regional and local policy incentives—such as LEED certification programs, mandatory carbon disclosure laws, and decarbonization initiatives—may influence the types of materials selected for embodied carbon estimates. This could explain why the West region, including states like California and Washington, showed significantly lower concrete embodied carbon area densities compared to other regions. These states are widely recognized for their progressive environmental policies, compared to other U.S. states, and early adoption of sustainable practices in procurement. As an example, in 2024, California updated their CALGreen, also known as Title 24 of the California Code of Regulations, to emphasize the need to reduce embodied carbon, especially for non-residential buildings over 100,000 sqft (Singh, 2024). It is these types of policies that can accelerate the adoption of EPDs, incentivize lower-carbon concrete solutions, and drive collaboration across the supply chain.

Nevertheless, this trend is not uniformly reflected across other progressive regions. The Northeast, for example, is also known for strong sustainability commitments and dense urban markets with ambitious climate goals. However, the projects in this region showed some of the highest embodied carbon intensities in the dataset. This raises the question about how much influence local market dynamics, infrastructure type demand, and material supply chains have on embodied carbon in the built world. Furthermore, it could suggest that simply having progressive policy frameworks in place may not be sufficient enough or may be lagging in adoption activities. Practical implementation, supply chain

collaboration, and the availability of low-carbon materials could be factors in the adoption of these policies. Further investigations into regional differences could offer valuable insight into how policy, practice, and embodied carbon performance are – or are not – aligned across North America.

6.2 Recycled Concrete Aggregate and Circularity

As noted, concrete is a significant contributor to C&D waste worldwide. However, while large volumes of it still end up in landfills, North America is making strides at diverting this material through recycling (*Advancing Sustainable Materials Management: 2018 Fact Sheet*, n.d.). In fact, industry data shows that over 60% of concrete waste from C&D in the U.S. is successfully reused or repurposed, most commonly as RCA (*Advancing Sustainable Materials Management: 2018 Fact Sheet*, n.d.). Still, the recycled material is primarily used in non-structural applications—such as roadbase, backfill, and asphalt mixtures—rather than being incorporated back into new structural concrete. This reveals an important distinction within circularity: while the material may be 'recycled', it is important to distinguish whether the 'recycled' material is reintroduced into the same supply chain or diverted into a completely different material stream with a new use (i.e., reuse). Nonetheless, either process constitutes as a valid circular strategy with reuse serving as a prioritized option for end of life. Still, the downcycling option of concrete challenges the notion of "closing the loop" in a material's life cycle, and it continues to put pressure on limited raw resources. Therefore, the industry's current use of RCA does not embrace the full potential of achieving material circularity for concrete. However, I posit that the

industry is ready to change in this regard given they're provided a path toward economic viability while circularizing.

The literature review in this study demonstrated that RCA can be successfully implemented into new concrete mixes under the right conditions, and that innovation in this area is growing. Across all studies, embodied carbon performance of RCA concrete was found to be heavily influenced by local conditions, such as aggregate source location, recycling facility location, transportation efficiency, and vehicle fuel type. These limitations indicate that the adoption of RCA concrete at a scale (e.g., across all U.S. regions) remains a challenge. This finding creates an opportunity for future research and planning around regional aggregate flow mapping. Understanding the location of C&D waste generation, concrete recycling facilities, and aggregate supply chains could help identify the regions that would be best suited for RCA utilization in concrete, specifically from a transportation and logistics perspective. Reducing and optimizing travel distances for recycled aggregates could significantly lower overall embodied carbon. Consequently, adoption and optimization of RCA concrete is not only a matter of technical performance, but also of logistical efficiency and regional resource planning.

Nonetheless, RCA replacement led to more pronounced environmental benefits in other impact categories, including ozone depletion, acidification, and resource depletion, across all studies reviewed. This indicates that RCA can meaningfully contribute to broader environmental sustainability goals, even when embodied carbon reductions alone may be modest.

Nevertheless, aggregate replacement on its own is not sufficient to significantly reduce the overall environmental footprint of concrete. Cement still remains the largest contributor to concrete's embodied carbon. Thus, meaningful progress towards a sustainable concrete requires a more comprehensive approach. Combining RCA with additional reduction strategies, such as the use of low-carbon binders, offer the greatest potential for impact. Ultimately, it is this dual strategy that will be key to lowering concrete's environmental burden at scale.

Overall, continued innovation in mix design, investment in local recycling infrastructure, and policy incentives for RCA adoption will all play a critical role in moving the industry toward a more sustainable and lower-carbon future for concrete.

6.3 Assessing Circularity with the Material Circularity Indicator

To complement the embodied carbon analysis conducted in this research and offer a more quantitative evaluation on material sustainability, this study employed the MCI developed by the Ellen MacArthur Foundation. The results of the MCI analysis revealed a notable hierarchy in circularity among the five common construction materials included in this study. Notably, concrete received the lowest MCI score from the list, which aligns with current industry trends. Despite concrete's relatively moderate recyclability, which scores over 50%, and the growing use and demonstrated potential of RCA, these efforts alone are not enough to raise concrete's overall circularity potential above a 0.4 score out of 1.0. In contrast, materials like steel and asphalt score significantly higher, in the ranges of 0.730 and 0.798, due to their well-established recycling systems and direction towards closed-

loop reuses. These finding indicate how concrete's performance in circularity is lagging, not due to lack of potential, but because of how it is currently used and recovered in the industry.

One key insight from the MCI results is that improving concrete's circularity requires a dual strategy, one that addresses both recycled content and end-of-life recovery. Focusing on just one of those aspects is not sufficient to enhance circularity scores significantly. This distinction mirrors the conclusions drawn from the RCA literature review, which emphasizes that recycled concrete must be part a combined approach to achieve embodied carbon reduction: increasing use of RCA and optimizing binder strategies. While the MCI and RCA findings pertain to different sustainability dimensions, namely circularity and embodied carbon, they converge on a similar message: single-point interventions are in insufficient. In both cases, a combined strategy is essential for making concrete more sustainable across its life cycle.

The results from the MCI analysis demonstrate it is a valuable metric that can complement embodied carbon evaluation. While embodied carbon focuses on the quantification of emissions, MCI provides insight into material flows and long-term efficiency. Together, these tools can help identify more targeted and comprehensive strategies for reducing the environmental burden of construction materials.

Nonetheless, the MCI framework is not without limitations. For example, the integration of certain design strategies guiding circularity—such as Design for Disassembly (DfD) or Design for Manufacture and Assembly (DfMA) (Goddin et al., 2019) is not clearly accounted for within the MCI methodology. Both approaches can

significantly enhance materials' recoverability and reuse potential, yet their influence may not be fully captured in the MCI equation. Future research could explore how design intent—as in which components enable separation and flexible reuse—might be integrated into a circularity scoring system such as MCI.

Additionally, while MCI offers a quantitative approach to evaluating material circularity, its application may benefit from a complementary qualitative approach. Since a material's circularity potential is influence by a range of contextual factors—such as regional supply chains, local recovery infrastructure, and design properties—incorporating a qualitative layer could help better interpret MCI scores and ensure strategies are tailored toward specific situations and goals. Future studies might explore the development of such hybrid frameworks to better guide sustainable material selection in complex, real-world conditions.

CHAPTER 7. CONCLUSION & RECOMMENDATIONS

7.1 Summary

As the climate crisis intensifies, increasing efforts have been directed toward mitigating the environmental impacts resulting from human activities and development. In particular, the built environment has been found to be one of the largest contributors to global GHG emissions, both through the energy used to operate buildings and the carbon emissions associated with the life cycle of a building. The focus of this thesis was to analyze the impacts associated with the latter, exploring how embodied carbon and material circularity intersect in new building construction. Concrete was treated as a primary area of study due to its outsized contributions to GHG emissions in this sector.

Drawing on a review of academic literature, an analysis of data from over 65 real-world projects, and the application of an established circularity methodology, this research assessed how different strategies influence environmental impacts. The findings confirmed that concrete consistently accounts for the largest share of embodied emissions, and that various strategies exist that can reduce emissions significantly and enhance material sustainably. A key conclusion of this research is that improving the sustainability of concrete requires integrated strategies that address multiple dimensions simultaneously, including material sourcing, mix design optimization, and regional recycling practices. Notably, the analysis revealed clear regional differences in embodied carbon outcomes across North America. Projects located in the Southeast and Northeast exhibited higher embodied carbon for concrete, which may be attributed to factors such as material sourcing, logistics, regional code requirements, climate adaptions, and differences in construction

practices. In contrast, projects in the West showed comparatively lower values, potentially reflecting broader adoption of lower-carbon concrete solutions and even deviation from concrete altogether. These variations underscore the need for context-specific strategies that reflect the unique material, logistical conditions, and policy adaption rates of each region.

Overall, this study serves as a liaison between academic research and industry practice, offering insights into real-world trends and providing a framework for translating academic insights into actionable strategies for the built environment.

7.2 Limitations

While this study offers valuable insights into embodied carbon and circularity trends, several limitations should be acknowledged. First, the industry dataset is based on construction document developed during preconstruction, rather than as-built records. As such, estimates reflect early design intent and may vary with further design development. Second, the dataset was limited to only five primary materials, which largely represent the structural core of buildings, but it excludes other possible significant contributors such as finishes, mechanical, electrical and plumbing (MEP) systems, and temporary construction materials.

Additionally, the scope of emissions evaluated in the industry data was limited to the Product stage (A1-A3 of Figure 1), omitting emissions from the Construction stage (A4-A5) and Use stages (B1-B5). Furthermore, embodied carbon estimates were each

generated by different professionals using various take-off tools and individual judgment. Subjectivity due to this approach could lead to variability in the consistency of carbon data. Another key limitation was the potential bias within the dataset's regional and typological composition. Certain regions may be overrepresented by specific building types, which can skew regional embodied carbon trend. Likewise, if a building type was only present a limited number of times, conclusions drawn about that building type may not apply broadly. Finally, the literature review conducted on RCA did not follow a formal systematic methodology which may have affected the insights of this part of the study.

7.3 Recommendations

This research opens several pathways for future research and industry action. One promising area lies in regional analysis: future works could benefit from exploring how embodied carbon trends align with climatic conditions, building resilience strategies, and local environmental responses. Comparative studies on regional policy assessments could help clarify how regulation influences design and material choices, which affect emissions. Similarly, evaluation of regional supply chains and transportation logistics could further explain variations in embodied carbon performance. There is also value in expanding research across building typologies. Sector-specific benchmarks and trends – such as for healthcare, commercial, or industrial – could help improve the accuracy and contextual relevance of embodied carbon baselines, as well as tailor specific strategies towards their environmental impact mitigations.

From an industry perspective, increasing data sharing is essential. This study was made possible through data access from a general contractor that, like several others in the industry, has committed to quantifying its carbon footprint. The next step is openness – sharing this type of data with government agencies and researchers can unlock deeper trend analyses and help accelerate innovation across the sector. Increased reporting and transparency will also support data harmonization, allowing the industry to move towards standardized methods and benchmarks.

In addition to material embodied carbon reporting (A1-A3), several general contractors—including the industry partner in this research—have begun tracking construction-phase emissions. Integrating these efforts into the LCA frameworks would allow the industry to expand the scope of analysis from A1-A3 to A1-A5. This is a critical next step, as emissions from transportation (A4) and construction (A5) activities remain largely unaccounted for in the academic and industry worlds.

Stronger collaboration between researchers, industry professionals, and policy makers can ensure that emerging strategies are both informed by practice and applicable at scale. While embodied carbon tools continue to evolve, aligning their utilization with industry workflows will support broader adoption. Ultimately, the influence of these efforts by the construction industry can create a reinforcing cycle—constructions teams gain clarity on what is feasible, demonstrate support for design-phase sustainability goals, and, in turn, empower clients to set or strengthen their own climate commitments. By feeding into this cycle, the industry as a whole can drive more sustainable choices for clients, stakeholders, and communities. Supporting this momentum is critical as the climate crisis demands urgent action and collective commitment now more than ever.

APPENDIX A. SELECTED LITERATURE REVIEW SOURCES

#	Article Name	Author(s)	Journal	Category	Year	Study Focus
1	A Building Life-Cycle Embodied Performance Index—The Relationship between Embodied Energy, Embodied Carbon and Environmental Impact	Hu, M.	Energies	Challenges and Trends	2020	Development of a life-cycle embodied performance (LCEP) index to assess energy-carbon-environment tradeoffs
2	A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings	Moncaster, A M and Song, J-Y.	International Journal of Sustainable Building Technology and Urban Development	Assessment Methods	2012	Comparison of databases and LCA methods for embodied carbon in UK and European buildings
3	A systematic investigation into the methodological variables of embodied carbon assessment of buildings	Pan, W. and Teng, Y.	Renewable and Sustainable Energy Reviews	Assessment Methods	2021	Analysis of how 11 methodological variables affect embodied carbon results across 244 building studies
4	An analytical method for evaluating and visualizing embodied carbon emissions of buildings	Resch, E. et al.	Building and Environment	Assessment Methods Case Study	2020	Analytical framework for assessing and visualizing embodied carbon in building subparts
5	An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework	Monahan, J. and Powell, J.C.	Energy and Buildings	Case Study	2011	Case study comparing embodied carbon of timber MMC and traditional housing

						construction in the UK
6	Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China	Zhanga, X. and Wang, F.	Energy and Buildings	Case Study	2017	Hybrid LCA with temporal weighting for embodied carbon in Chinese residential buildings
7	Assessment of embodied carbon emissions for building construction in China: Comparative case studies using alternative methods	Zhanga, X. and Wang, F.	Energy and Buildings	Assessment Methods	2016	Comparison of process-based, input-output, and hybrid methods for embodied carbon in Chinese buildings
8	Benchmarking the Embodied Carbon of Buildings	Simonen, K. et al.	Technology |Architecture + Design	Fundamentals & Basics	2017	Creation and analysis of the largest known building embodied carbon benchmark database
9	Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects	Cottafava, D. and Ritzen, M.	Resources, Conservation & Recycling	Circular Economy	2021	Development and testing of building circularity indicators integrating design-for-disassembly and embodied impacts
10	Circularity Indicators: An Approach to Measuring Circularity, Methodology	James Goddin, et al.	Ellen MacArthur Foundation	Circular Economy	2019	Development of Material Circularity Indicator (MCI) for product and company-level circularity assessment

11	Comparison of the Embodied Carbon Emissions and Direct Construction Costs for Modular and Conventional Residential Buildings in South Korea	Jang, H. et al.	Buildings	Reduction Strategies	2022	Comparison of embodied carbon and cost for modular vs. RC residential buildings in South Korea
12	Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings	Gan, V.J.L. et al.	Journal of Cleaner Production	Assessment Methods Circular Economy	2017	Embodied carbon analysis method for high-rise buildings using procurement scenarios
13	Developing Buildings' Life Cycle Assessment in Circular Economy-Comparing methods for assessing carbon footprint of reusable components	Joensuu, T. et al.	Sustainable Cities and Society	Circular Economy	2022	Comparison of three LCA methods for assessing reusable building components in a circular economy context
14	Development of a material circularity evaluation framework for building construction projects	Amarasinghe, I. et al.	Journal of Cleaner Production	Circular Economy	2024	Framework using FAHP to rank material circularity criteria in buildings aligned with ReSOLVE
15	Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure	Hawkins,W. et al.	Structures	Case Study	2021	Dynamic LCA comparison of concrete, steel, and timber buildings using time-based climate metrics
16	Embodied carbon emissions in buildings: explanations, interpretations, recommendations	Lützkendorf, T. and Balouktsi, M.	Buildings and Cities	Fundamentals & Basics	2022	Policy and design recommendations for assessing and reducing embodied carbon in buildings

17	Embodied Carbon Reduction Strategies for Buildings	Kumari, L.M.T. et al.	University of Maratuwa	Reduction Strategies	2020	Literature-based review of global strategies to reduce embodied carbon in buildings
18	Embodied energy and carbon in construction materials	Hammond, G.P., and Jones, C.I.	Proceedings of Institution of Civil Engineers	Fundamentals & Basics Assessment Methods	2008	Development and application of a UK embodied energy and carbon material database
19	Embodied energy of buildings: A review of data, methods, challenges, and research trends	Rahman Azari, Narjes Abbasabadi	Energy and Buildings	Challenges and Trends	2018	Review of embodied energy methods, material impacts, and reduction strategies in buildings
20	Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation	Martin Röck, Marcella Ruschi Mendes Saade, Maria Balouktsi, Freja Nygaard Rasmussen, Harpa Birgisdottir, Rolf Frischknecht, Guillaume Habert, Thomas Lützkendorf, Alexander Passer	Applied Energy	Challenges and Trends	2020	Global meta-analysis of 238 LCAs assessing embodied vs. operational GHG emissions in buildings

21	Estimation and Minimization of Embodied Carbon of Buildings: A Review	Akbarnezhad, A. and Xia, J.	Buildings	Fundamentals & Basics Reduction Circular Economy	2017	Review of embodied carbon estimation methods and reduction strategies across building life cycle
22	How does concrete and cement industry transformation contribute to mitigating climate change challenges?	Fateh Belaïd	Resources, Conservation & Recycling Advances	Challenges and Trends	2022	Decarbonization strategies for the cement and concrete industry with a focus on Saudi Arabia
23	Initiatives to Report and Reduce Embodied Carbon in North American Buildings	De Wolf, C. et al.	Embodied Carbon in Buildings - Book	Fundamentals & Basics	2018	Overview of embodied carbon reports in buildings in North America.
24	Life Cycle Assessment of Embodied Carbon and Strategies for Decarbonization of a High-Rise Residential Building	Alotaibi, B.S. et al.	Buildings	Reduction Strategies	2022	LCA of a high-rise residential building in India with BIM-integrated decarbonization strategies
25	Life Cycle Assessment of Embodied Carbon in Buildings: Background, Approaches and Advancements	Khan, S.A. et al.	Buildings	Fundamentals & Basics Reduction Circular Economy	2022	Review of embodied carbon LCA methods, uncertainty modeling, and mitigation strategies
26	Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database	Dräger, P. et al.	Environmental Sciences Europe	Circular Economy	2022	Application of an adapted MCI method to assess product circularity in the German ÖKOBAUDAT database
27	Measuring embodied carbon dioxide equivalent of buildings: A	De Wolf, C. et al.	Energy and Buildings	Assessment Methods	2017	Critique of embodied carbon assessment

	review and critique of current industry practice					practices across academia and industry
28	Minimising upfront carbon emissions of steel-framed modular housing: A case study	Kechidi, S. and Banks, N.	Journal of Building Engineering	Case Study Reduction Strategy Circular Economy	2023	Roadmap for reducing upfront embodied carbon in steel-framed modular housing
29	Operational vs. embodied emissions in buildings—A review of current trends	T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye	Energy and Buildings	Challenges and Trends	2013	Critical review of embodied vs. operational emissions trends in lifecycle building assessments
30	Reducing embodied carbon during the design process of buildings	Häkkinen, T. et al.	Journal of Building Engineering	Reduction Strategies	2015	Framework for integrating embodied carbon decisions across RIBA design stages
31	Reducing embodied carbon in concrete materials: A state-of-the-art review	Chen, S. et al.	Resources, Conservation & Recycling	Reduction Strategies RCA	2023	Systematic comparison of EC reduction potentials for low-carbon concrete materials (LCCMs)
32	Reducing embodied carbon in structural systems: A review of early-stage design strategies	Fang, D. et al.	Journal of Building Engineering	Reduction Strategies	2023	Review and classification of early-stage design strategies to reduce structural embodied carbon

33	Scrutinising embodied carbon in buildings: The next performance gap mademanifest	Pomponi, F. and Moncaster, A.	Renewable and Sustainable Energy Reviews	Assessment Methods	2018	Meta-analysis of embodied carbon data variability and design-stage performance gaps
34	Statistical analysis of embodied carbon emission for building construction	Kang, G. et al.	Energy and Buildings	Case Study	2015	Probabilistic modeling of embodied carbon using statistical analysis of Korean building materials
35	The Status of Embodied Carbon in Building Practice and Research in the United States: A Systematic Investigation	Hu, M. and Esram, N.W.	Sustainability	Fundamentals & Basics Assessment Methods	2021	Systematic review of embodied carbon methods, data, and tools in U.S. building practice
36	Trends toward lower-carbon ultra-high performance concrete (UHPC) – A review	Zhang , X. et al.	Construction and Building Materials	Challenges and Trends RCA	2024	LCA-based assessment of low-carbon material strategies for UHPC mixtures
37	Using life cycle assessment to achieve a circular economy	Peña, C. Et al.	International Journal of Life Cycle Assessment	Circular Economy	2021	Position paper on aligning LCA frameworks with circular economy strategies
38	Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures	Hart, J. et al.	Journal of Industrial Ecology	Fundamentals & Basics Case Study	2021	Systematically comparison of the whole-life embodied carbon (WLEC) of 127 multistory building superstructure designs across steel, reinforced

						concrete (RC), and engineered timber systems.

APPENDIX B. SAMPLE OF PROCESSED INDUSTRY DATA

#	Anonymized Building Name	Abbr.	City	State	Region	Building Use	Area (sqft)	# of Stories	Height (m)	Realized EC (kgCO2e)	Concrete EC (kgCO2e)	Steel EC (kgCO2e)	Asphalt EC (kgCO2e)	Glass EC (kgCO2e)	Wood EC (kgCO2e)
1	Peru Goshawk 4	PG4	Toms River	New Jersey	Northeast	Industrial	31,810	1	13	3,015,710	1,994,461	927,959	84,483	8,808	-
2	Maroon Woodpecker 52	MW52	Vaughan	Ontario	Canada	Data Center	131,630	1	14	4,647,194	2,578,719	1,910,030	90,380	65,269	2,797
3	Green Ferret 44	GF44	Toronto	Ontario	Canada	Educational	58,015	5	35	2,328,903	1,277,114	629,457	103,493	304,401	14,437
4	Violet Stingray 92	VS92	Surrey	British Columbia	Canada	Institutional - Healthcare	2,449	3	14	1,134,511	1,034,971	41,722	27,989	23,454	6,374
5	Sienna Dugong 44	SD44	Baltimore	Maryland	Northeast	Office	33,500	3	22	1,233,433	666,319	385,801	32,329	143,608	5,375
6	Violet Boar 4	VB4	Frederick	Maryland	Northeast	Data Center	575,970	0	8	22,661,122	14,755,673	6,910,130	990,096	-	5,222
7	Blue Lapwing 60	BL60	Spotsylvania Courthouse	Virginia	Southeast	Data Center	249,973	2	19	9,591,322	5474187	3,803,539	200,683	110,353	2,561
8	Thistle Shrew 48	TS48	Cincinnati	Ohio	Midwest	Residential.Multi-Unit	509,189	15	49	15,054,521	11,749,172	2,633,295	237,406	358,302	76,346
9	Red Stinkbug 24	RS24	Lexington	Kentucky	Southeast	Educational	276,160	5		8,041,918	4,155,079	3,153,171	596,808	74,168	62,691
10	Bisque Seahorse 0	BS0	Sandusky	Ohio	Midwest	Data Center	444,255	2	0	8,085,977	7,423,650	245,419	390,856	25,917	135

APPENDIX C. SELECTED LITERATURE ON RCA

#	Article Name	Author(s)	Journal	Year	Study Focus
1	Recycled Concrete Aggregates: A Review	McNeil, K. & Kang, T.H.K.	International Journal of Construction and Building Materials	2013	Performance and mechanical properties of RCA in concrete
2	A Recycled Aggregate Concrete High-Rise Building: Structural Performance and Embodied Carbon Footprint	Xiao, J. et al.	Journal of Cleaner Production	2018	Structural and environmental performance of a real RCA high-rise building
3	Comparative Assessment of Embodied Energy of Recycled Aggregate Concrete	Wijayasundara, M. et al.	Journal of Cleaner Production	2017	Embodied energy analysis of RAC vs. NAC using hybrid LCA
4	Low Carbon Concrete Possibilities: EPD and Regulations in Northern Periphery and Arctic	Novakova, T. et al.	Material Proceedings	2023	Evaluation of EPD and low-carbon concrete strategies in Nordic countries
5	Transforming Construction and Demolition Waste Concrete as a	Rodriguez-Morales, J. et al.	Resources, Conservation and Recycling	2024	Use of recycled concrete fines as precursors in alkali-activated binders

	Precursor in Sustainable Cementitious Materials: An Innovative Recycling Approach				
6	Multicriteria Analysis of Environmental and Economic Performance of Circularity Strategies for Concrete Waste Recycling in Spain	López Ruiz, L.A. et al.	Waste Management	2022	Environmental and economic comparison of circular concrete strategies in Spain
7	Performance Enhancement of Recycled Concrete Aggregate – A Review	Shi, C. et al.	Journal of Cleaner Production	2016	Review of techniques to improve RCA quality for use in concrete
8	Combination of LCA and Circularity Index for Assessment of Environmental Impact	Kadawo, A. et al.	Journal of Sustainable Cement-Based Materials	2023	LCA and circularity index for evaluating RAC environmental impacts
9	Embodied Carbon of Concrete in Buildings, Part 1: Analysis of Published EPD	Anderson, J. & Moncaster, A.	Buildings and Cities	2020	Analysis of EPDs for cementitious materials and ready-mix concrete

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