Decarbonization of Concrete Structures: A Path Towards Industrialization

By

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ABSTRACT

The increasing demand for more efficient and eco-friendly building practices has led to developing and improving traditional construction methods to address building issues concerning environmental impacts and costs. However, alongside the incorporated benefits, they introduce new obstacles and challenges that impact the final product. Alternatives to decrease carbon dioxide emissions by reducing construction materials usage are strongly emerging in the industry due to environmental harm and its impact on climate change. In many developed countries such as Canada, different acts and measures are being taken to achieve net-zero emissions shortly, fostering a collaborative commitment across the industry to eliminate millions of tonnes of greenhouse emissions.

This study employs building information modeling technologies and examines six construction methods regarding material usage, carbon footprint, and costs. This approach analyzes basement walls methods: Insulating Concrete Form (ICF) walls, concrete sandwich wall panels, ribbed wall panels, and concrete slabs: cast-in-place, hollow-core, and ribbed slabs to assess material cost implications and carbon footprint of reinforcement steel, insulation, formwork timber, and concrete in the manufacturing, transportation, and material waste, stages.

The study aims to identify the most sustainable and cost-effective construction practices by comparing these methods under consistent project conditions, constraints, location, and transportation distances.

The findings indicate significant mitigation of carbon emissions and cost savings with ribbed structures. However, these benefits may vary depending on construction location, transportation distances, material types, site temperature conditions, choice of manufacturers, and seismic activity. The study highlights the need for continuous innovation to meet environmental goals and ensure economic viability.

PREFACE

This thesis is an original work by Alejandro Ramon Rivera. The research of which this thesis is a part received research ethics approval from the University of Alberta Research Ethics Board, project name "Decarbonization of Concrete Structures: A Path Towards Industrialization".

ACKNOWLEDGMENTS

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LIST OF ABBREVIATIONS

Abbreviation	Full Expression
CO_2	Carbon Dioxide Emissions
ICF	Insulating Concrete Form
BIM	Building Information Modeling
LCA	Life Cycle Analysis
CO_2e	Carbon Dioxide Emissions equivalent
RC	Reinforced Concrete
MEP	Mechanical, Electrical, and Plumbing
CRD	Construction, Renovation and Demolition
CIP	Cast-in-place
PC	Prestressed Concrete
VOCs	Volatile organic compounds

CHAPTER 1: RESEARCH MOTIVATION AND OBJECTIVES

1.1 Research Motivation

The construction industry currently faces a critical need to address carbon emissions generated to the environment, spurred by legislative measures such as the "Canadian Net-Zero Emissions Accountability Act." Given the critical environmental impact of conventional construction materials such as concrete and reinforcement steel, this legislation underscores the critical need for more sustainable building practices. The target is to eliminate more than 15 million tons of greenhouse gas emissions cumulatively by 2030.

Reinforced concrete, for instance, accounts for a significant portion of global industrial emissions due to its material's manufacturing process. Concerning concrete alone, emissions are mainly generated from chemical reactions in the cement production needed for converting limestone into clinker and the fossil fuel emissions generated to produce the high temperatures required to achieve this process (Government of Canada, 2022). Similarly, manufacturing one ton of reinforcement steel requires large quantities of water (nearly 28 tons) and more than twice the amount of energy than cement production (Javier Yanes, 2023).

However, technologies such as BIM-based software like Adobe Revit offer promising ways to facilitate the assessment and mitigation of carbon footprint by accurately modeling building structures and extracting detailed material volumes. These are crucial inputs to calculate embodied carbon in building components; with this information, designers can identify opportunities to optimize material usage, select low-carbon alternatives, and implement suitable construction practices to reduce emissions in preliminary designs.

This study employs structural designs in a Building Information Modeling environment through Adobe Revit to analyze three construction methods for basement walls: Insulating Concrete Form (ICF) walls, concrete sandwich wall panels, and ribbed wall panels, and three building practices for concrete slabs: cast-in-place slabs, hollow-core slabs, and ribbed slabs. By assessing the carbon footprint and costs of material, this research aims to provide insights into embodied carbon in Life Cycle Assessment (LCA) stages that comprehend cradle-to-pre-construction phases such as material manufacturing (A1-A3), transportation to the site (A4), and material waste(A5w), as well as identify cost implications and building systems with the best cost-effectiveness.

1.2 Study Objectives

The thesis's main objectives are the following:

- **Objective 1.** Identify possible restrictions and/or limitations in the structural design of structures.
- **Objective 2.** Provide a fair comparison of the construction practices by designing structures based on the case studies' project criteria, data, and constraints.
- **Objective 3.** Model precise details of structures in the Above Revit to extract exact volumes of materials.
- **Objective 4.** Assess the carbon emissions of each building practice and identify Life Cycle Analysis stages and materials with the most embodied carbon in the system.
- **Objective 5.** Identify the most cost-effective building practices and provide detailed insights into the cost contributions of each construction material.
- **Objective 6.** Highlight the carbon emissions and costs introduced by formwork structures used in each construction system and the importance of looking for other alternatives.
- **Objective 7.** Provide an overall comparison of practices for basement walls and concrete slabs to facilitate the identification of the most cost-effective and least environmentally impactful methods.

1.3 Thesis Organization

The thesis consists of six chapters, structured as follows:

Chapter 2 provides a literature review on decarbonization, Building Information Modeling (BIM) Technologies as a Tool to Facilitate CO2 Emissions Assessments, and construction systems comparison.

Chapter 3 introduces the construction methods considered for this research, describing the construction process, the components of each structure, the advantages and disadvantages related to the research framework, and the formwork used for their construction.

Chapter 4 outlines and describes the methodology followed in the thesis, the case studies, the approach, and the techniques implemented in this study.

Chapter 5 focuses on the results of implementing the methodology. It provides detailed results for each construction method and compares carbon emissions and costs generated by construction materials and related formwork. Additionally, it provides restrictions identified when designing Insulating Concrete Form Walls.

Chapter 6 concludes the thesis by providing the study's overall conclusions and outlining contributions, limitations, and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Decarbonization

In response to growing environmental concerns, the construction industry is experiencing an increasing trend of studies assessing the environmental impacts of construction processes. The literature shows two common characteristics: (1) Comparison, including offsite and onsite construction, to identify opportunities for reducing carbon emissions through Analysis of Life Cycle Assessment in Buildings (LCA), and (2) concentration on the use of alternative materials, specifically in concrete and reinforcement steel as a solution for the mitigation of embodied carbon.

For example, Jang et al. (2022) compared embodied carbon emissions of modular and conventional residential buildings in South Korea. This research approach identified the difference in environmental impact emissions during the material production stage through consultations of major drawings and design details to calculate the input quantities of construction materials for the assessment. Results revealed that modular construction approaches led to a notable reduction of approximately 36% in embodied carbon emissions compared to traditional reinforced concrete methods (Jang et al., 2022) .Similarly, a study by Kamali et al. (2019) examines the environmental performance of traditional onsite and modular off-site construction methods in the residential building sector through a cradle-to-gate LCA. Even though results from three family buildings used as study cases show that offsite building techniques demonstrated lower environmental impacts than onsite construction methods, authors suggest that neither modular nor conventional construction is inherently superior in terms of environmental friendliness. However, optimal designs and material reduction could mitigate environmental impacts for both approaches (Kamali et al., 2019).

Tosti et al. (2018) on the other hand, provide insights into the role of decarbonization of concrete and mortars injecting biomass fly ash. This study consisted of replacing specific percentages of cement for ashes from renewable organic material and then testing for compressive strength, concluding that fly ash as a cementitious material is a promising solution for decarbonization in concrete structures (Tosti et al., 2018) .Similarly, research done by Al-Khafaji et al. (2019) investigated the performance of sand-coated glass fiber rebars in concrete to introduce a solution for corrosion-free materials and minimize the footprint caused by the use of reinforcement steel in the construction industry.

By analyzing different approaches in the literature associated with the environmental impacts of current construction techniques, it becomes evident that strategies aimed at mitigating carbon emissions primarily revolve around reducing building material consumption and embracing alternative materials while ensuring structural integrity. However, despite numerous research in this area, there remains a noticeable gap in studies directly contrasting embodied carbon in specific construction practices in basement walls and concrete slabs utilizing the methods assessed in this thesis. This gap presents an opportunity for further exploration better to understand the environmental implications of current building practices in Canada.

2.2 Building Information Modeling (BIM) Technologies as a Tool to Facilitate CO2 Emissions Assessments

Building Information modeling technologies have emerged as powerful tools, especially in the construction industry. They offer advanced capabilities for digital representation and analysis of building projects. Specifically, BIM models enable the development of detailed structure designs, facilitating fast and precise estimation of material requirements, which are the primary input information for any carbon emissions analysis.

Mazur & Olenchuk (2023), for instance, explored the impact of the building design of traditional masonry construction and timber frames regarding carbon footprint in single-family houses. This study uses ArchiCAD and Eco Designer Star plugin to simulate and assess the energy performance during their manufacturing process. Using this approach, key factors influencing carbon footprint emissions were identified for each station. Likewise, Li et al. (2020) assessed the carbon emissions in the materialization phase of prefabricated concrete buildings in China, which integrates carbon emission factors into BIM technology, allowing for computations of footprint in different construction phases. The study findings concluded that prefabricated concrete structures emit significantly less CO2 than other types of buildings.

Additionally, they rank materials based on carbon footprint in the following order: cement, steel, concrete, and wire.

Crippa et al. (2018) address a comparison of 4 popular wall systems in the Brazilian market: clay brick masonry, concrete block masonry, steel frame, and wood frame, using a framework that integrates BIM and LCA to analyze each of their contributions to the embodied carbon footprint. This approach facilitated fast computations of materials from different construction techniques and designs to identify high-emission contributors during construction stages.

In light of BIM technologies' potential in assessing CO2 emissions, this research aims to provide an analysis through the application of Autodesk Revit. This approach extends beyond traditional methodologies to provide a comprehensive analysis of carbon emissions in certain LCA stages across different construction methods and design scenarios.

By leveraging Autodesk Revit's advanced capabilities for detailed structure design and precise material estimation, this study will facilitate a more accurate and efficient evaluation of the carbon footprint associated with various construction techniques. Additionally, integrating Revit into an LCA analysis will enable the identification of high-emission contributors during different stages of the building lifecycle, thus providing critical insights for sustainable construction practices.

Furthermore, this research will contribute to the existing body of knowledge by offering a comparative analysis of traditional and modern construction materials and methods. The findings from this study are expected to support industry stakeholders in making informed decisions to reduce construction activities' environmental impact. Ultimately, integrating BIM and LCA in this research underscores the importance of innovative technologies in promoting sustainability and addressing the pressing issue of climate change within the construction industry.

2.3 Construction Systems Comparisons

Despite extensive research on these two construction methods, no comparative studies directly evaluate Insulating Concrete Forms (ICF) and Precast Concrete Sandwich Panels. The existing literature primarily focuses on one or the other, often highlighting energy conservation benefits and structural design optimizations within each method.

For example, Lu & Memari (2019) provide valuable insights into the energy efficiency and environmental benefits of ICF in cold climates compared to wood-frame structures. Their research underscores ICF's potential for significant long-term energy savings and environmental benefits, using detailed building simulations to validate these findings . On the other hand, their study does not address how ICF compares to alternative systems for basement walls, like concrete sandwich panels or ribbed walls. It can be assumed that the study mainly focuses on above-grade walls since comparisons are made with wooden-frame walls.

Similarly, Faria Oliveira et al. (2022) offer a detailed analysis of the structural and thermal performance of concrete sandwich panels; specifically, they analyzed 20 panels and found they vary widely in their bending strength, weight per square meter, and thermal efficiency. They discovered that alternative binders instead of traditional Portland Cement can significantly enhance eco-efficiency. However, their comparative framework does not include ICF walls or other concrete practices.

This gap in the literature indicates a need for comparisons between these three prominent construction methods. By evaluating both ICF and Precast Concrete Sandwich Panels side by side, this research aims to provide an understanding of their respective costs and environmental impacts. Specifically, it seeks to determine which method offers greater eco-efficiency and cost-effectiveness. This involves assessing not only their initial construction costs and associated carbon emissions from the structure, but also their related formwork.

On the other hand, studies comparing concrete slabs primarily focus on structural performance, optimization of structural designs, and span ranges. Only a few studies include ribbed slabs and hollow core slabs in their analyses. Moreover, there is a noticeable gap in studies that incorporate both costs and carbon emissions of formwork materials in their comprehensive assessments. In contrast, some studies focus solely on either costs or carbon emissions.

Paik & Na (2019) conducted a study assessing the CO2 emissions of three slab systems: ordinary reinforced concrete slabs, flat plate slabs, and voided slabs. Their assessment spans from cradle to pre-operation. They concluded that manufacturing building materials was the main contributor to these emissions, with reinforcing bars and formwork materials being particularly significant in flat plate and voided slab systems. The voided slab system demonstrated the greatest potential for CO_2 reduction, suggesting that alternative slab systems can substantially reduce emissions in building projects.

Similarly, Kong et al. (2020) studied the carbon emissions from the material production phase and construction phase of cast-in-place slabs and precast slabs. Contrary to most studies, they found that carbon emissions increased during the production and transportation stages due to the mechanical operations and the weight of prefabricated components.

However, during the on-site construction, carbon emissions significantly decreased due to lower hoisting frequency and reduced on-site pouring. This indicates that while prefabrication may increase emissions in some stages, it offers considerable reductions during on-site construction.

Despite these valuable insights, there is still a lack of comprehensive studies that compare the costs and environmental impacts of different slab systems, including ribbed and hollow core slabs, emphasizing the full lifecycle of the materials used. This research aims to fill this gap by providing an analysis that includes economic and environmental factors, thereby offering a complete understanding of the sustainability and cost-effectiveness of various slab systems. By doing so, it contributes to the body of knowledge on sustainable construction practices and helps guide future decisions in the industry.

CHAPTER 3: CONSTRUCTION METHODS AND TECHNIQUES

This chapter introduces the construction methods and techniques assessed in this research, focusing on concrete basement walls and above-ground concrete slabs. Section 3.1 discusses different types of concrete basement walls, beginning with Insulating Concrete Form (ICF) walls, concrete sandwich panels, and ribbed wall panels. On the other hand, in Section 3.2, various types of concrete slabs are examined: cast-in-place slabs, hollow core slabs, and ribbed slabs.

A detailed description of the construction methods, construction process, advantages, and disadvantages are discussed for each building practice. Additionally, section 3.3 of this chapter covers the essential role of formwork in concrete construction, including its types, construction process, and associated costs and hazards.

This comprehensive overview provides a solid foundation for understanding the construction methods evaluated in the research.

3.1 Concrete Basement Walls

Concrete basement walls or foundation walls are a fundamental component in building construction. They provide structural support to the above levels and create a barrier against soil and water. These walls are typically built using reinforced concrete due to their mechanical durability and resistance to harmful exterior agents, such as pests, water, and fire.

This section analyzes onsite and offsite construction methods, highlighting various techniques employed in constructing concrete basement walls to understand their processes, benefits, and potential challenges.

3.1.1 Insulating Concrete Form Walls

Insulating concrete form (ICF) is an on-site construction method used only for wall erection, eliminating the need for formwork. Two courses of insulation blocks, which provide high thermal resistance, serve as molds to pour fresh concrete, as illustrated in Figure 1. These blocks are held by plastic “ties” or “connectors” and are crucial in ensuring the rebar's correct alignment and spacing. Figure 2 illustrates a wall panel after rebar placement.

ICF walls, a product of post-World War II innovation, initially made from wood fiber and plastic blocks, have evolved to incorporate insulation boards (Salvia, 2021). This evolution was driven by the need to meet regional constraints such as extremely low temperatures, particularly in cold areas like Canada. The recognition of ICF walls in the National Building Code of Canada, (Government of Canada, 2020), in 2005 (CAN/ULC-S717.1-12, "Standard for flat wall insulating concrete form units) and in the International Residential Code in 2006 in the United States marks a significant milestone in the acceptance of this construction method.

Despite its recognition into North America's most important building codes, this method was incorporated with several restrictions. For instance, The National Building Code of Canada (NBCC) states that buildings constructed with ICF above or below grade wall panels cannot have a greater area than 600m^2, a maximum floor height of 3 meters, and more than two-story building height. Additionally, particular rebar requirements, such as specific distribution and placement into connectors, are specified to comply with the code.

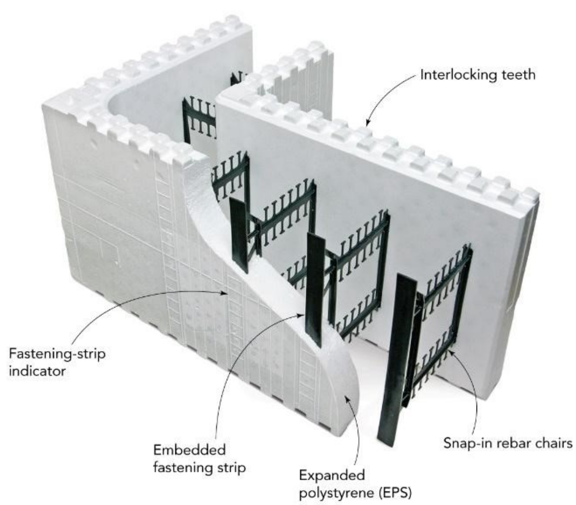


Figure 1:Insulating Concrete Form Block (Fine Homebuilding, 2023).

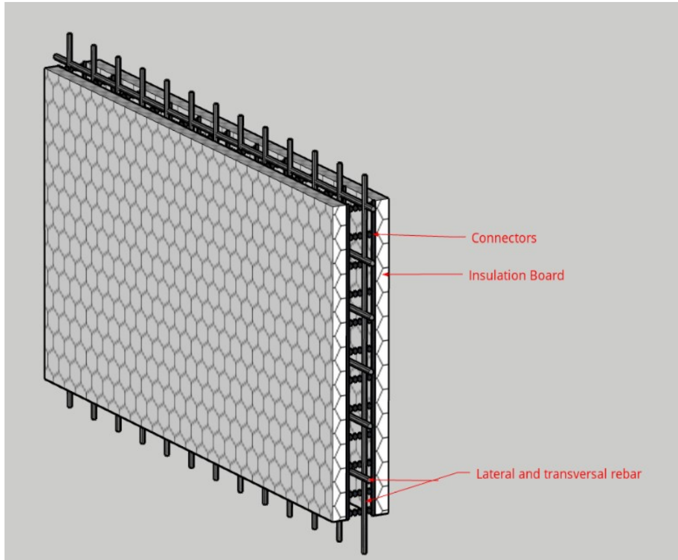


Figure 2: Insulating Concrete Form panel after rebar placement.

The construction process of this cast-in-place construction method consists of erecting the building footings beforehand and then continues with the ICF block placing and stacking. After ensuring the correct alignment, placement, and stacking of ICF forms, reinforcement steel is placed with the help of connectors, which provide a system that facilitates its proper installation. Interior and exterior bracing of the walls are placed before the concrete pouring to give stability and support, avoiding collapses of the structure until the concrete hardens. After the process of pouring, vibrating, and leveling of concrete, installation of the floor is performed (usually wooden frame slab). For this stage, a transition ledge is installed after the concrete is placed, typically at the floor level, where a wider ICF wall narrows above the floor line and up to the roof.

Eventually, when all the structure is done, Interior and exterior finishes occur. ICF walls need protection against humidity. Thus, a moisture barrier is installed on both sides of the wall to avoid structural degradation, corrosion issues, and mold and mildew growth. Figure 3 shows the manufacturing process, equipment, and material used for ICF walls.

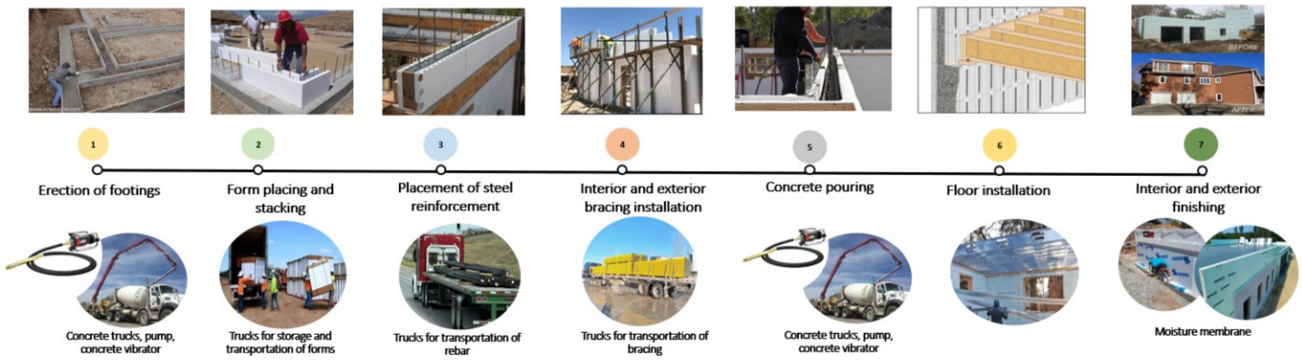


Figure 3:Construction process of basement ICF walls and equipment needed for each stage, data collected from ICF Builder Magazine (2016), Roberts (2020) and Waterproofing ICF foundations (2023).

Some advantages of this construction method are using molds that replace traditional formwork. This makes the construction of elements easier, quicker, and more practical. The plastic connectors not only hold both layers of insulation, but allow a simple and standardized reinforcement steel installation, thus reducing the reliance on skilled labor, as the assembly becomes a straightforward and less intense process. This practicality contributes to decreased labor costs and the likelihood of errors and inconsistencies.

However, ICF walls have drawbacks and potential consequences that must be evaluated. One significant issue is high material costs. Additionally, the environmental impacts, space utilization limitations, building code constraints, and aesthetic concerns are important considerations.

Regarding environmental impacts, since this is an onsite construction method, all equipment, materials, and labor must be transported to the site. This transportation contributes to environmental carbon emissions and soil, water, and air pollution. Toxic chemicals from concrete and other construction materials, such as silica dust, volatile organic compounds (VOCs), and chromium, can leach into the soil and reach aquifers. Furthermore, the disposal of polystyrene foam at the site can lead to contamination. When burned, polystyrene foam emits gases that release toxins, causing several health problems, particularly affecting the human nervous system.

On the other hand, incorporating two insulation courses on both sides of the concrete wythe significantly reduces space utilization. Insulation in ICF walls goes from 2 inches to 4 inches thick for each board, meaning that in addition to the concrete layer of 8 inches, another 4 to 8 inches of space will be taken by polystyrene foam in the wall, resulting in a total wall thickness of at least 12 inches or up to 16 inches.

While constructing ICF walls eliminates formwork, insulation boards that serve as molds for wet concrete are not strong enough to support and stabilize the wall while the concrete is fresh. Consequently, bracing on both sides of the walls is needed to avoid misalignments and collapses, which increases the costs and risks of improper bracing erection. Figure 4 shows a misaligned ICF wall caused by the incorrect installation of the bracing system.

Figure 4: Issues caused by incorrect bracing during concrete placement (Roger Normand, 2018).

3.1.2 Concrete Sandwich Panels

Concrete sandwich panels are a precast construction method that consists of two layers of concrete separated by a low-density core with insulation properties. As shown in Figure 5, the concrete layers are categorized into two: the facial or outer layer, which provides protection to the structure from outdoor phenomena and gives aesthetics to the building's facade within different finishings, and the interior wythe of concrete, which is known as the structural wall. This layer is the primary load-bearing element, providing stability, strength, and continuity to the panel. The third layer, placed in the middle of the concrete courses, is typically made of polystyrene foam; its functionality relies on enhancing the thermal performance of the panel and avoiding heat transfer through the concrete layers.

The panel's layers' thickness usually vary depending on design factors. The facial concrete layer typically ranges from 2 to 3 inches, followed by the middle layer of the insulating core, which can be 2 to 6 inches thick, depending on the desired thermal performance. Finally, the third layer ranges from 4 to 8 inches since it serves as the primary load-bearing element of the panel.

Moreover, shear connectors are installed to connect and achieve a composite action in both concrete wythes. Their characteristics, such as shape, placement, and spacings, vary depending on specific design requirements, the designer, and the manufacturer. These connectors are crucial as they ensure a composite behavior of the panel, allowing it to act as a single unit under load rather than separate layers.

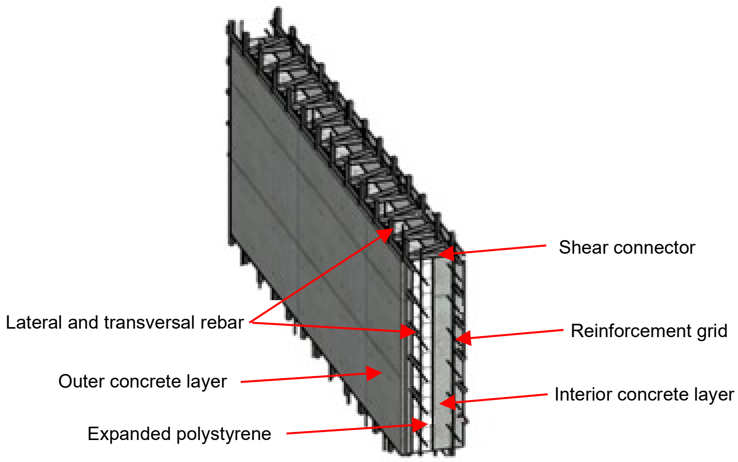


Figure 5: Concrete sandwich panel detailing.

Its manufacturing process consists of various stations, as shown in Figure 6, from the erection of the formwork and concrete cast off-site to the transportation and installation of the wall panels on the construction site. Forming is first built in the factory, usually made of timber or steel, to install reinforcement such as grids, bars, and shear connectors, and eventually cast the first concrete wythe. Once the concrete has hardened, the polystyrene foam course is placed, then the same process is repeated for the second concrete layer. After the second wythe of concrete has adequately cured, panels are lifted by a crane to a trailer and transported to the site, where another crane will be needed for their installation.

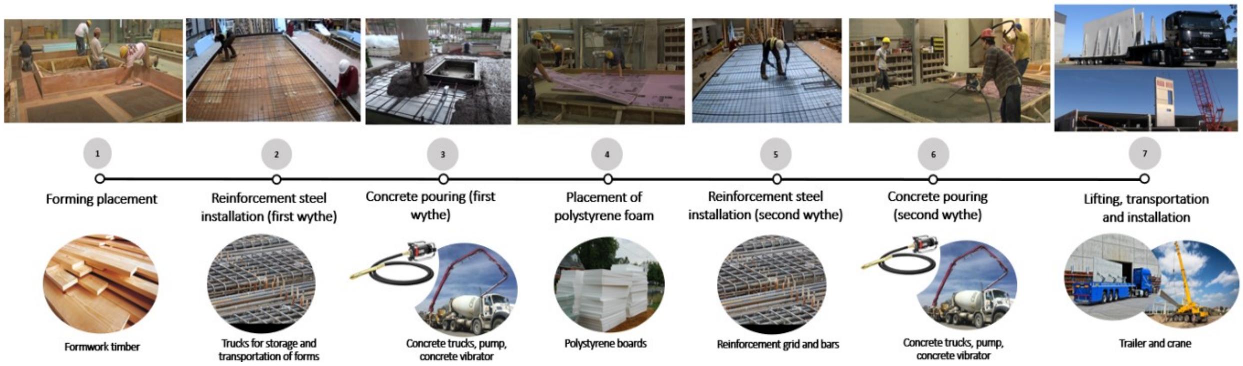


Figure 6: Basement sandwich panel manufacturing process, equipment, and materials, data collected from Elematic (2016) and Lafarge Precast Concrete Edmonton (2017).

One significant consequence of material consumption and carbon emissions in constructing concrete sandwich panels is the requirement for additional reinforcement steel, such as shear connectors. These connectors are essential to achieving the composite action between the panel layers, ensuring the structure performs as a unified element under load. However, including these shear connectors necessitates larger volumes of reinforcement material, which substantially increases the panels' embodied carbon and cost.

Furthermore, the exterior layer of the concrete sandwich panel is crucial for providing aesthetic appeal and protection from environmental elements; this outer layer primarily enhances the visual appearance of the building’s facade. Consequently, the material used for this non-structural layer represents an overconsumption of resources, which could otherwise be minimized to reduce the overall carbon footprint of the construction.

3.1.3 Ribbed Wall Panels

Ribbed Wall Panels are precast panels featuring a series of ribs designed to optimize the structural efficiency of walls. The incorporation of ribs enhances the panels' strength and rigidity, allowing for a significant reduction of construction material usage without compromising the structural integrity. Offering savings of costs and environmental impact.

For a detailed description of this construction practice, consult section 3.3. Ribbed Slabs and Wall panels.

3.2 Concrete Slabs

Concrete slabs are essential structures that provide a sturdy and level building surface. Depending on the project specifications, they are typically built using either wood or reinforced concrete.

This section analyzes onsite and offsite construction methods of above-grade concrete slabs used for this study, highlighting their construction process, advantages, and potential disadvantages.

3.2.1 Cast-in-place Slabs

Cast-in-place or cast-in-situ slabs shown in Figure 7, are a conventional onsite construction method consisting of pouring concrete at the site in a formwork. This differs from precast construction practices cast in a factory and assembled at the construction site.

Cast in place of structures is an ancient, well-known and the most used method for constructing any type of structure worldwide. It facilitates the construction of monolithic structures with minimal joints, allowing for flexibility in design and modifications during and after the construction process.

Monolithic construction refers to a uniform, single-poured structure. This unified structure allows for an even distribution of loads across the entire surface, enhancing durability by reducing cracking and structural stability.

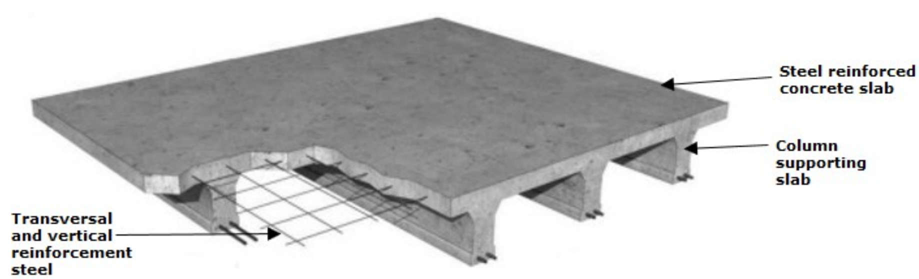


Figure 7: Cast-in-place continuous supported slab.

Figure 8 shows its construction process, which starts with constructing, preparing, and setting formwork on the site. Forms are usually made of lumber and plywood and nailed together. After the formwork is installed and secured, formwork oil is applied to prevent dry concrete from sticking and allow for easy removal of the timber. At the same time, rebar is placed within the formwork, thus providing tensile stress to the structure.

Concrete mix can be done on-site or transported from the manufacturing location to the construction site. Once the concrete mix is on the site, it is poured, compacted, and leveled to eliminate air, voids, and bubbles until the desired texture is achieved. Concrete is then cured for several days until it develops its full strength and durability. Finally, formwork is removed when the concrete is dry and ready to carry loads.

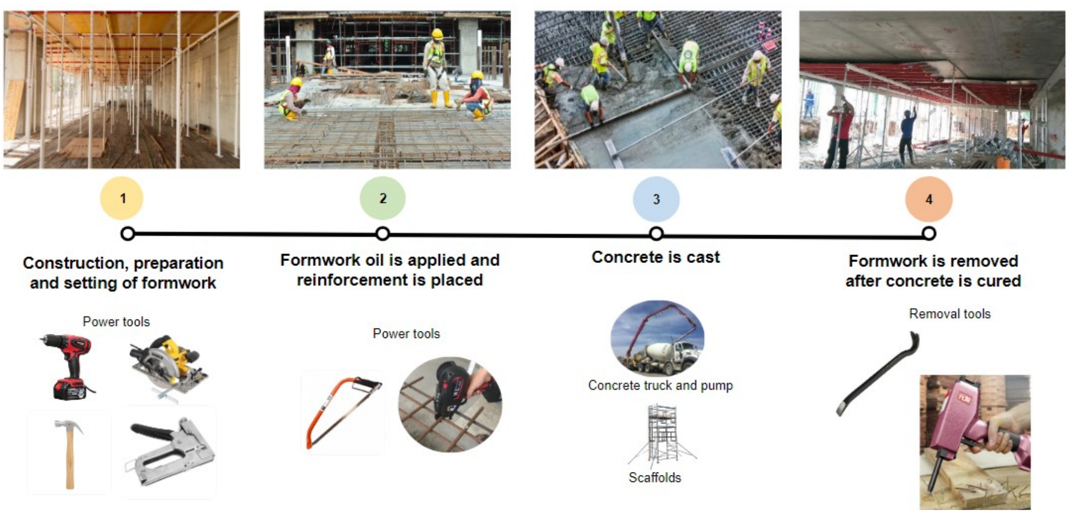


Figure 8: Cast-in-place concrete slab construction process, data collected from Alsina (2022), and The Constructor (2018).

One of the drawbacks of cast-in-situ concrete structures is their reliance on formwork, which is needed to hold the reinforcement in place, shape the concrete, and support concrete weight while it is still fresh. This not only significantly contributes to extra construction time and costs but also increases carbon emissions from the manufacturing of materials used for formwork, such as steel or timber, and extra construction operations, such as transportation that comprehends the hauling of material to the site from the storage facility and vice versa, exacerbating the carbon footprint and overall environmental burden of the project.

3.2.2 Hollow Core Slabs

Hollow-core or voided slabs combine cast-in-place and precast prestressed concrete flooring systems in above-grade slabs. They account for the peculiar characteristic of hollow cross sections created by oval or circular voids along the panel. These voids are the product of eliminating building material in the neutral axis of the structure, where it does not contribute to the structural integrity. This design allows hollow-core slabs to maintain the same load-bearing capacity as solid slabs while minimizing the use of concrete in non-critical areas.

Hollow-core slab reinforcement consists of high-strength tendons or strands tensioned by jacks on both extremes before concrete pouring. This helps counteract the tensile stresses when the structure is in use and significantly enhances its strength and durability. Once prestressed tendons are cut after the concrete is cast, the tensile strength properties occasioned by the reinforcement tension are transferred to the concrete, allowing a higher load capacity to the system.

As depicted in Figure 9, the hollow-core slab system comprises hollow-core planks manufactured in a factory to be transported and installed on the site. Once in place, a concrete topping, typically averaging 6 inches in thickness with a regular reinforcement grid, is cast over the planks. This composite layer primarily integrates the structure and distributes loads within the floor system. It binds the individual planks together, creating a monolithic floor that helps distribute loads evenly across the entire surface.

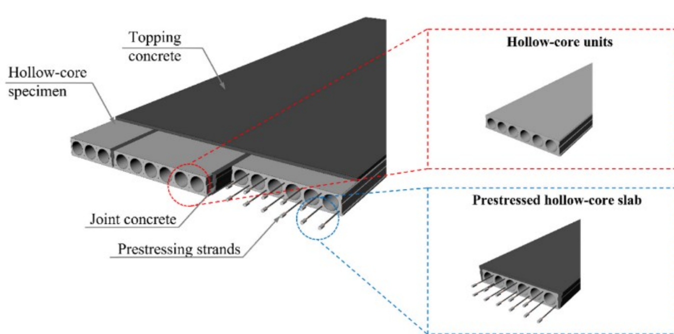


Figure 9: Hollow-core slab system detailing (Heo et al., 2021).

The construction process, illustrated in Figure 10, starts with placing high-tensile strands in steel plates that serve as molds for the planks' voids. Then, strands are pre-tensioned with hydraulic jacks. Depending on the factory's technological capabilities, this activity can be carried out manually or automatically.

After properly tensioning the strands, the next step involves creating circular voids within the planks. This is achieved using a concrete extruder, which shapes the concrete around the pre-tensioned strands and ensures that the voids are evenly distributed along beds extending up to 120 meters long.

Following the extrusion process, the concrete is allowed to cure. Once cured, the long beds are cut into the desired length of planks, which are transported to the construction site for installation.

Once all the hollow-core planks are placed on the structure, formwork and reinforcement are prepared and installed on top of them. This preparation is crucial for pouring a solid concrete layer, unifying the system.

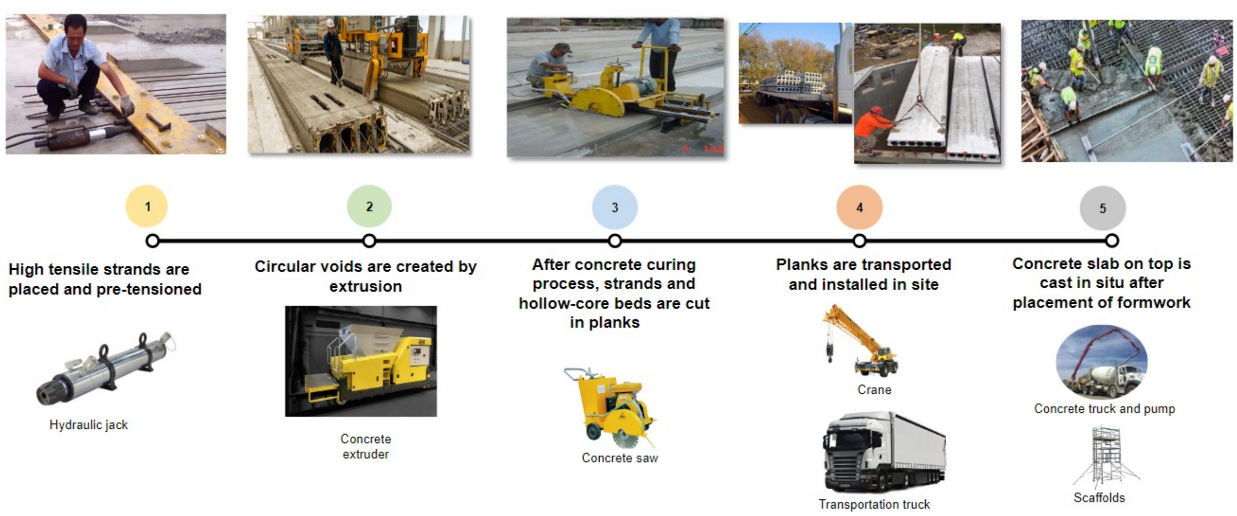


Figure 10: Hollow-core slab system construction process, data collected from Factory Monster (2023), India Precast (2014), and The Constructor (2018).

The hollow-core slab system offers both advantages and disadvantages. One notable drawback is the extensive use of heavy equipment and specialized activities, which pose significant risks to worker safety and contribute to embodied carbon from construction

operations. Using concrete extruders, cranes, forklifts, and hydraulic jacks increases the environmental impact and adds complexity to the construction process. Additionally, the need for cast-in-place concrete pouring on top of the planks and its associated formwork compounds the environmental footprint and construction challenges.
On the other hand, the major advantage is the reduction of material consumption. By eliminating the excess material in the neutral axis, this method helps mitigate some carbon dioxide emissions compared to conventional construction practices.

3.2.3 Ribbed Slabs

Ribbed slabs are precast concrete panels distinguished by a network of ribs integrated into a thin concrete layer or shell. This construction method aims to create lighter, more cost-effective slabs by reducing the required building materials.

By decreasing the weight of the panels, ribbed slabs can efficiently span larger distances, thereby improving structural capacity and versatility. Additionally, the reduced weight lessens the loads transferred to other structural elements, potentially allowing for smaller and more economical supporting structures. This design optimizes material usage and enhances the overall efficiency and sustainability of the construction process.

Section 3.3, "Ribbed Slabs and Wall Panels," provides more details about this construction practice, including the construction process, advantages, and disadvantages.

3.3 Ribbed Slab and Wall Panels

Ribbed panels are an off-site construction method that incorporates parallel ribs that extend along the wall length, consisting of a 2-inch shell thickness panel. This is due to eliminating non-necessary material in the system at the neutral axis (where the stress is zero).

The structure consists of precast concrete reinforced with a reinforcement grid in the 2-inch shell, vertical rebar running along the ribs, and horizontal bars at the top and bottom sides of the panel. Styrofoam is used to give the wall insulation properties, being installed on the interior side of the wall on the ribs and shell, as depicted in Figure 11.

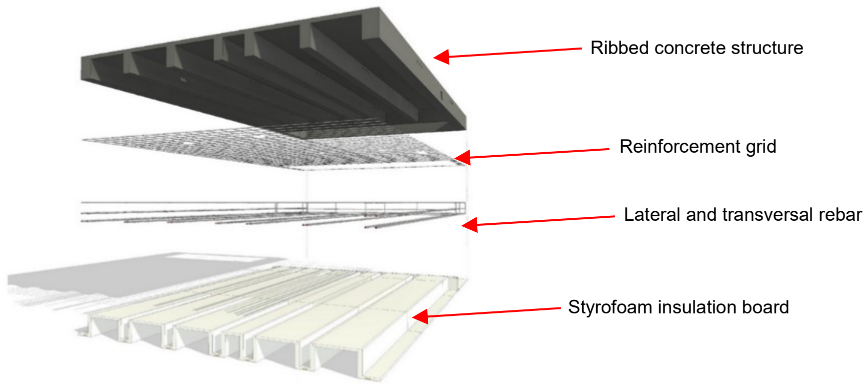


Figure 11: Ribbed panel components.

This construction method is applied to walls and slabs, as both share the same construction process, principles, and logic. The primary differences typically lie in the rib's dimensions, including thickness, height, and spacing. Figure 12 shows the typical dimensions of ribbed slabs and walls.

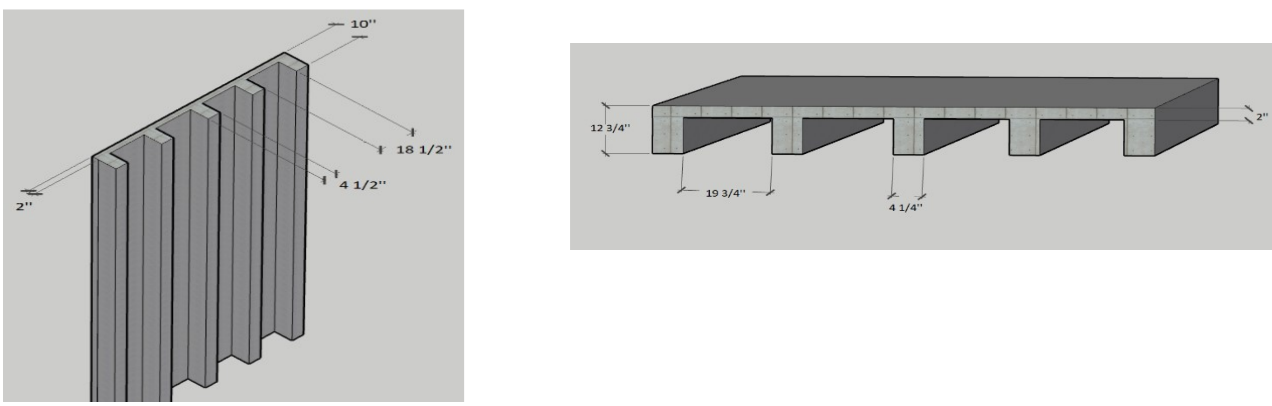


Figure 12: a) Ribbed wall standard dimensions, b) Ribbed slab standard dimensions.

The manufacturing process, illustrated in Figure 13, starts with detailed project planning and coordination within departments such as production, drafting, design, and mechanical-electrical-plumbing teams. Structural design and definition of reinforcement, concrete, openings, and connections for MEP are well defined in the planning stage. After the final drawings are delivered, the production department starts erecting the forming to install reinforcement steel and Styrofoam boards and openings for MEP. Concrete casting occurs afterward; once panels are completely cured, they are lifted and placed in a trailer that would transport them to the site for a proper installation and erection of the building.

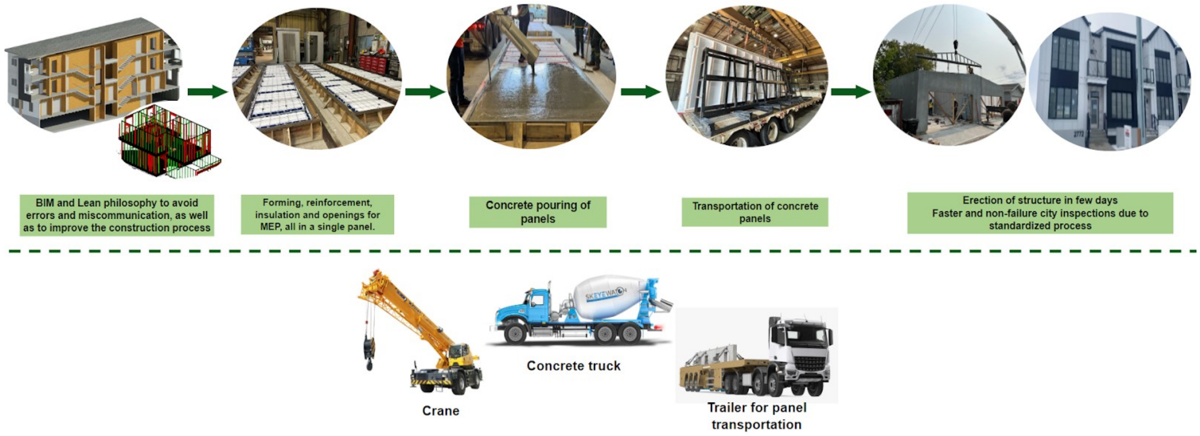


Figure 13: Ribbed slab manufacturing process and equipment, data obtained from 3i precast concrete (2023).

This construction practice offers advantages, including eliminating formwork and bracing. By using styrofoam for insulation around the panels that also work as molds, this method reduces costs and minimizes the carbon emissions typically generated by traditional formwork.

Furthermore, this method enhances mechanical, electrical, and plumbing systems by integrating styrofoam conduits into the panels before concrete casting. These conduits facilitate the easy installation of wiring, pipes, and HVAC ducts without wall chasing, concrete breaking, or surface-mounted lines. Such processes avoid structural damage and CO_2 emissions caused by material waste from demolition debris and the additional concrete required to cover wall cuts.

Moreover, eliminating construction materials in the neutral axis results in cost savings and CO2 emissions mitigation. This is because it reduces the materials needed for construction without compromising structural integrity. Consequently, it not only lowers material costs but also reduces the carbon footprint associated with the production and transportation of these materials.

3.4 Formwork

Formwork is an auxiliary structure made of timber or steel consisting of connected molds that temporarily carry and give shape to wet concrete until it hardens. As depicted in Figures 14 to 17, different formwork structures exist for different purposes, such as for building walls, slabs, foundations, stairs, columns, beams, etc. This activity has contributed to the construction of traditional and modern buildings, and it is considered a critical system for erecting, shaping, and connecting different structural components of a building.

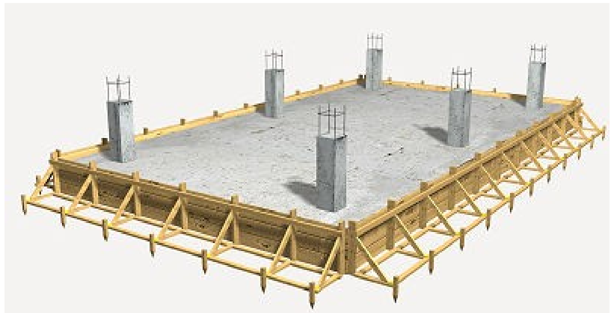


Figure 14:. Slab on grade formwork structure (Goconqr, 2020).

Figure 15: Cast-in-place wall formwork structure (Zaidan House, 2021).

Figure 16: Cast-in-place columns formwork structure (Aisyaqilumar, 2015).

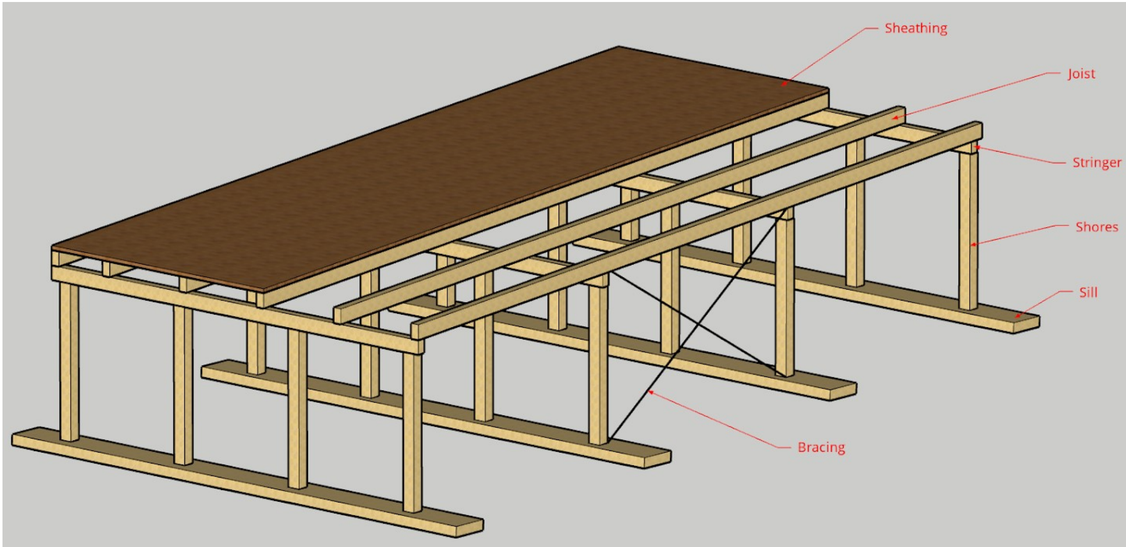


Figure 17:Traditional formwork structure for a concrete slab.

The most common types of formwork materials are timber and steel. Timber formwork is the most commonly used due to its adaptability and easy installation; however, it has a shorter lifespan than other materials. On the other hand, steel formwork is a durable and reusable material that also allows it to provide smoother finishes.

Traditional formwork involves connecting struts, sheathing, wales, bracing, shores, etc. In above-grade structures, these connections must be performed using different equipment to facilitate work at heights, such as scaffolds, ladders, and sometimes scissor lifts and boom lifts, as shown in Figures 18 to 20.

Figure 18: Use of boom lift for erecting column formwork (Ed Harris et al., 2023).

Figure 19: Use of ladder for erecting wall formwork (Alamy, 2019).

Figure 20: Use of scaffolds for concrete pouring (Kateryna Mashkevych, 2020).

The construction process of slab formwork, illustrated in Figure 21, consists of the design, planning, and selection of material, where the size, layout, and shape of formwork are determined based on the dimensions of the concrete element and loads that the form structure is meant to carry, as well as the selection of the material, such as timber dimensions, thickness of sheathing and quality. Transportation of the material to the site then takes place to perform the fabrication according to the designed dimensions and specifications. Besides, timber is treated typically by applying formwork oil to prevent concrete from sticking and ensure easy removal. Before concrete and steel are placed, formwork is properly erected, aligned, leveled, and secured with bracing to assure safety, stability, and stiffness when loads are applied. After the concrete is cured and hardened, the removal of formwork is performed carefully without damaging the concrete. When timber is properly cleaned, an inspection is needed to identify any damages and necessary repairs before storage and reuse. For safety reasons, they are discarded if timber members cannot be repaired or present poor quality.

Figure 21: Formwork construction process, data obtained from Dynajet (2021), and Adobe stock (2015).

Traditional formwork has multiple negative implications in terms of costs and time. According to a recent literature review by Terzioglu et al. (2021), the cost of formwork can typically account for up to 15% of the total expenses for a finished project, around 60% of the unit cost of reinforcement concrete (RC) structures, and between 50% and 75% of the total time spent on the construction of RC structures.

Additionally, several vital categories stand out within formwork hazards, such as falls, which represent a predominant concern since they are common, resulting from scaffolding and ladders. Additionally, collapses of concrete structures derived from the inefficient design and placement of formwork, although less frequent, often result in fatalities, making them a critical concern in the industry, affecting not only the injured worker but also the contracting company since these accidents introduce work disruption and variability to the process, causing time delays, possible liabilities and cost overruns.

The Workplace Safety and Insurance Board states that costs associated with an injury claim are nearly CA$12,000. Additional expenses related to the accident, such as loss of productivity, equipment damage, and delays, can rise to more than CA$59,000 depending on the damages (Work safety and prevention services, 2021).

Another problem concerning structures made of timber, such as formwork, is the potential environmental harm caused by their large amounts of material waste. In Canada, wood is the most predominant material waste, accounting for 59% of the country's total construction, renovation, and demolition (CRD) waste (Yeheyis et al., 2012). Annually, the construction industry in Canada produces about 9 million tons of CRD waste (Yeheyis et al., 2012). Consequently, it can be estimated that more than 5 million tons of waste are produced annually by timber in Canada. If this timber is not treated and recycled properly, it can negatively impact climate change, producing large amounts of methane, a powerful greenhouse contributor.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 Study Cases

Two 3i Precast Concrete LTD case studies were analyzed to evaluate and compare different construction methods' material usage and carbon footprint. These case studies focus on different structural components: basement walls and concrete slabs. This research consists of each method's structural design and 3D modeling in Autodesk Revit, all adhering to the original project's structural specification details and design. This study comprehensively explains various construction techniques' environmental impacts and material requirements, including concrete, reinforcement steel, insulation, and timber required for formwork.

4.1.1 Case Study 1: Basement Walls

The first case study involved a project of ribbed foundation basement walls for a one-story residential building 25.9 feet by 34.25 feet (see Figures 22 and 23). The 9-foot-tall basement walls were designed to support an upper story constructed with a wooden frame structure. The study compares the ribbed walls actual project case, with simulated construction methods, including Insulating Concrete Form walls and concrete sandwich panels.

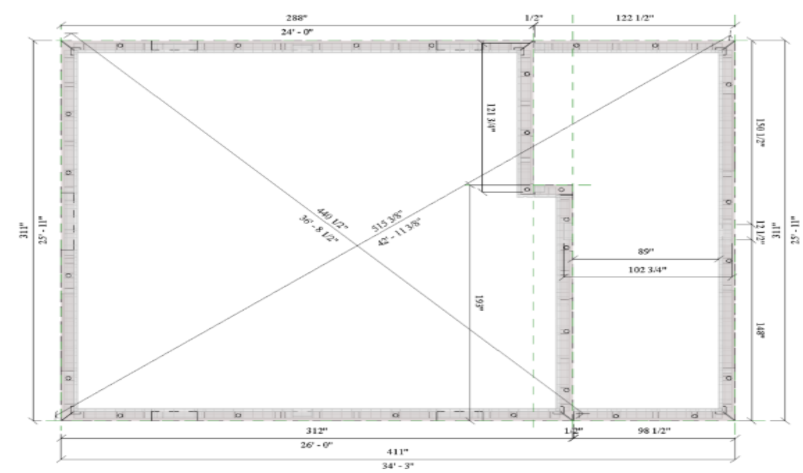


Figure 22: Basement walls, study case dimensions.

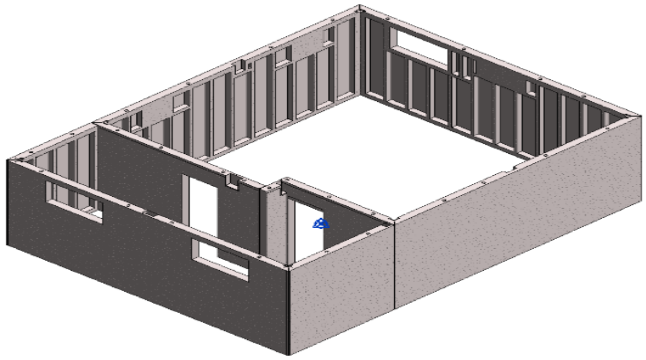


Figure 23: Basement walls, study case 3D model.

4.1.2 Case Study 2: Concrete Slabs

The second case study focused on a project involving the construction of a two-story residential building of 1081 square feet (See Figures 24 and 25). This project features two above-grade ribbed slabs of different dimensions, as shown in Figures 26 and 27. The actual project case of ribbed slabs is used to facilitate a comparison with simulated construction methods, including cast-in-place slabs and hollow core slabs.

Figure 24:Study case 3D model.

Figure 25:Concrete slabs to analyze.

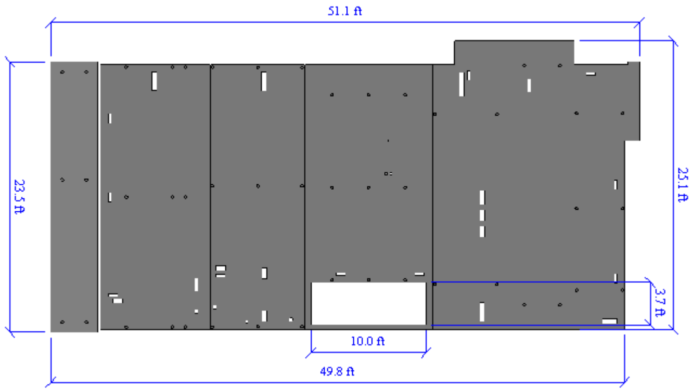


Figure 26: Main floor slab.

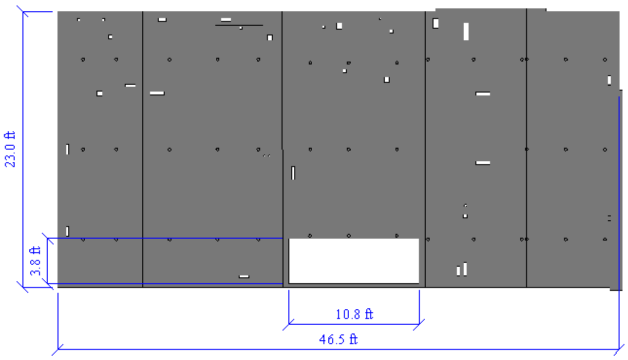


Figure 27. Second-floor slab.

4.2 Methodology Overview

The methodology used in this work is a comprehensive approach based on assessing carbon emissions and costs in six different construction practices for concrete basement walls and above-grade concrete slabs using a Building Information Modeling approach. This approach provides detailed insights of embodied carbon and costs of materials such as concrete, reinforcement steel, insulation, and timber used for formwork, ensuring the accuracy and reliability of our findings.

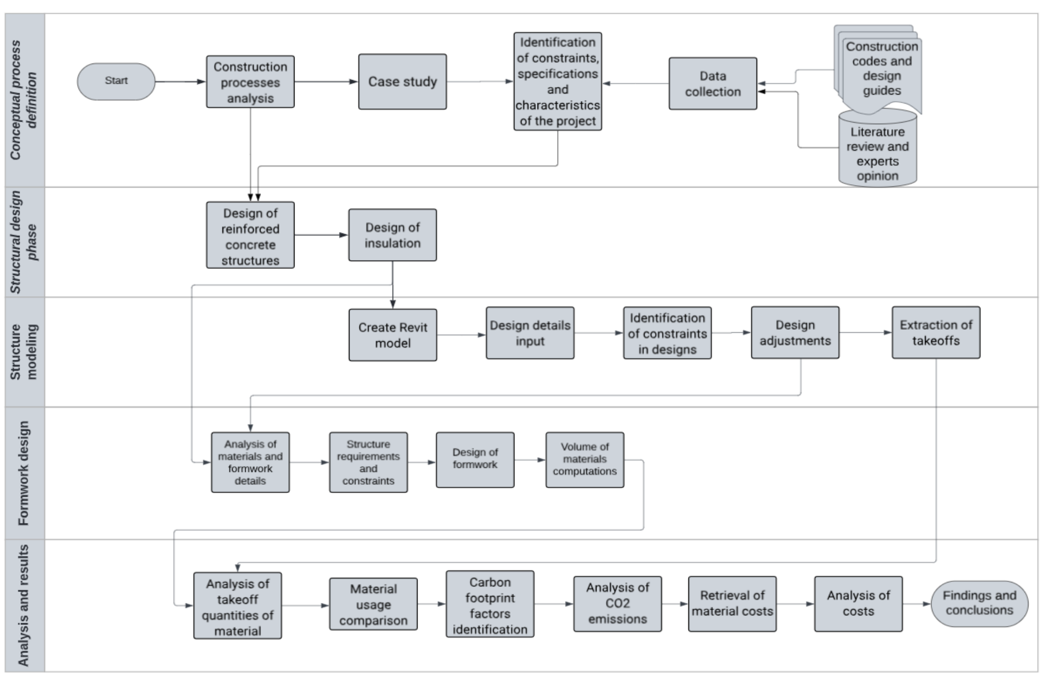


Figure 28: Methodology Framework.

Figure 28 provides an overall explanation of the implemented methodology. The initial steps include analyzing various construction methods, including possible advantages, disadvantages, and overall construction processes. Case studies were also selected and studied to identify the nature of the projects, specifications, and constraints.

The next step was replicating the ribbed walls using Insulating Concrete Form and concrete sandwich walls. Similarly, ribbed slabs are replicated into cast-in-place solid slabs and hollow-core slabs. This occurred during the structural design phase, which was performed based on data collection such as construction codes, consultation of designs in literature, and opinions from field experts. These structural designs would allow for a fair comparison by avoiding overdesign and meeting the same criteria and specifications as the original case studies. After designing all the structures, Adobe Revit was used to model these in a BIM-based environment that allows the user to input precise details, display elements in a 3D environment, and extract exact information such as material volumes.

Formwork designs were performed and included for those elements that require molding and support from an external structure. This requirement is dependent on each construction practice since not all need forming. Additionally, formwork material take-offs were computed and included in the respective method to start with carbon emissions and cost comparison.

Finally, the analysis involved identifying the embodied carbon factors of materials at each life cycle stage and material waste rates, analyzing construction operations, defining transportation distances, and retrieving material costs. This criterion was then used to compare results regarding carbon emissions and correspondent costs introduced by each construction method.

4.3 Insulating Concrete Form Walls Model

The structural design of ICF panels was performed based on the consultation of "The Insulating Concrete Forms Manufacturers Association Prescriptive ICF Design for Part 9 Structures in Canada" (Tacoma Engineers, 2021), and the National Building Code of Canada Alberta Edition (Government of Canada, 2020). The design of Insulating Concrete Form walls consisted of panels made of concrete of 35 MPa and grade 400 deformed rebar, 15M vertical reinforcement at 16 inches, and horizontal 10M rebars at 36 inches. Criteria considered for the design and modeling are shown in Table 1, followed by Figure 29, which illustrates its modeling in Autodesk Revit.

Table 1. Factors considered for selection of wall reinforcement.

ICF block height	18 inches
Tie spacing	8 inches
Thickness of wall (concrete)	8 inches
Thickness of each insulation board	2 ¾ inches
The overall thickness of the wall	13 ½ inches

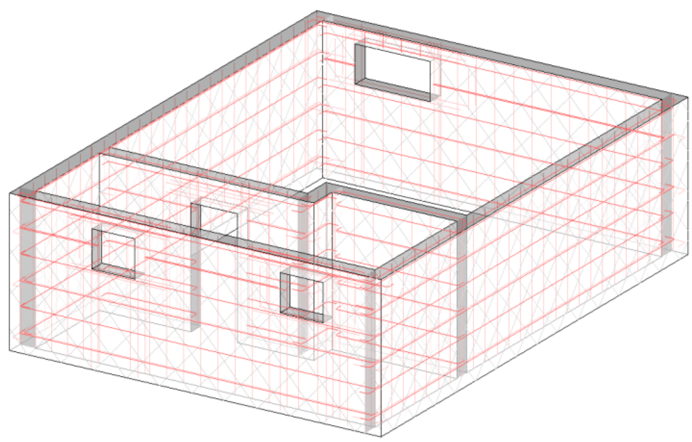


Figure 29:ICF model.

Additional requirements and adjustments were incorporated into the design based on the ICFMA manual's prescriptive ICF Design 2021, part 5.4, "Windows and door openings," as listed below.

- A minimum of 2-10M horizontal and vertical bars are to be installed around door and window openings.
- Distributed vertical reinforcing steel interrupted by an opening must be replaced by an equal amount of concentrated vertical reinforcing steel, half of which was placed on each side of the opening.

- The cumulative width of openings in below-grade walls is not more than 25% of the total wall length.
- Horizontal bars above and below the opening extend a minimum of 610mm (24 in) past the opening.
- Vertical bars on each side of the opening were extended to the full height of the wall.

Specifications stated in the ICFMA manual's prescriptive ICF Design 2021, part 5.1, "Distributed reinforcement steel," were considered as listed below.

- Addition of one continuous horizontal bar of 10M at a maximum of 150mm (6 in) from the top of the wall
- The reinforcement sizes and spacing selection were based on Table B.1.2. "Below Grade Wall Distributed Reinforcement." Inputs for tables included a wall height of 9 feet, a backfill height of 8 feet, and a maximum soil density of 480 kg/m3.
- The minimum concrete, clear cover, and reinforcement spacing are 1 ½ inches as a minimum.
- Standard hook lengths of a) 200 mm (8 in) for 10M bars, b) 250 mm (10 in) for 15M
- Alternating horizontal bar spacing of 12 and 24 inches on center was used to achieve an average spacing of 18 inches specified for horizontal bars, as shown in Figure 30.

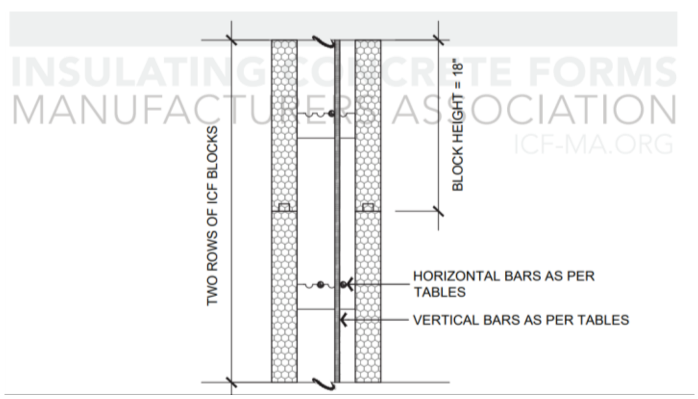


Figure 30: Horizontal bar spacing (Tacoma Engineers, 2021).

Other specifications, as stated in the National Building Code of Canada 9.15.4 "Foundation walls" and 9.20.17 "Above-Ground Flat Insulating Concrete Form Walls", were considered for this study, as listed below.

- Openings have a minimum distance of 1200mm from the corner of the wall.

- Openings over 600 mm but not more than 3,000 mm wide shall be reinforced at the top and bottom with one 10M bar.
- Openings wider than 3000 mm shall be reinforced on all four sides with two 10M bars.

4.4 Concrete Sandwich Walls Model

Characteristics and design details of sandwich wall panels shown in Table 2, such as the thickness of concrete wythes and insulation, were selected after carefully revising common Canadian industry standards, code specifications, and technical drawings in the literature.

On the other hand, secondary details such as reinforcement sizes and spacings, concrete compressive strength, shear connectors' locations, and shapes were selected based on literature specifically from Tomlinson & Fam (2015) and Mohamad et al. (2017) to be then modified to meet Canadian standards and specifications for basement walls stated in the National Building Code of Canada (NBCC) Alberta Edition. Figure 31 depicts the 3D model performed in Adobe Revit.

Table 2.Design criteria for sandwich wall panels.

Thickness of the interior concrete layer	5 inches
Thickness of the exterior concrete layer	3 inches
Thickness of insulation board	2 inches
Overall thickness of the wall	10 inches
Minimum concrete cover	1 ½ inches
Vertical and horizontal reinforcement in both layers	15M at 1000mm
Shear connectors	10M average spacing of 36 inches across the wall

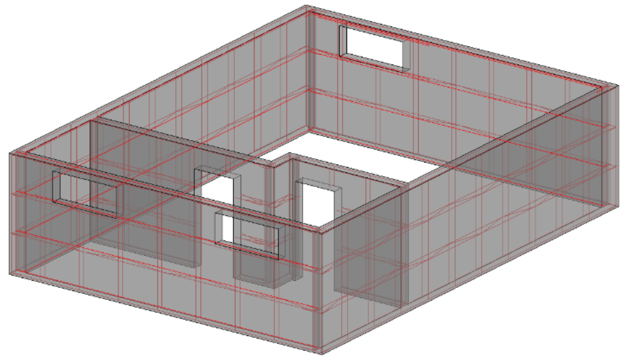


Figure 31:Concrete Sandwich panel model.

Specifications for shear connectors, including shape and anchorage details, were based on literature from Mohamad et al. (2017). These connectors are single steel elements bent at a 45-degree angle, inserted through the wythes and core layers of the sandwich wall, and tied to the steel reinforcement embedded in the wythes, as illustrated in Figure 32.

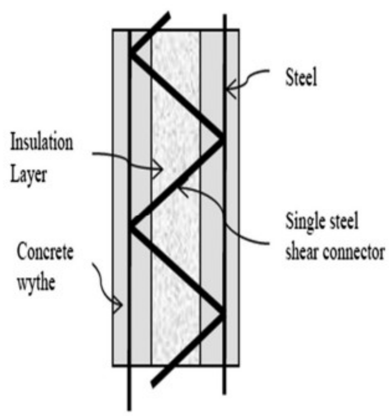


Figure 32:Single steel shear connector (Mohamad et al., 2017).

On the other hand, the spacing and positioning of the connectors were taken from Tomlinson D. & Fam. A. (2015). This study considers the spacing of shear connectors equivalent to half of the height of the wall, measured from the middle of the wall. Figure 33 shows the wall dimension and spacing of shear connectors considered in their study. Meanwhile, Figure 34 illustrates the same parameter applied to this research's wall height.

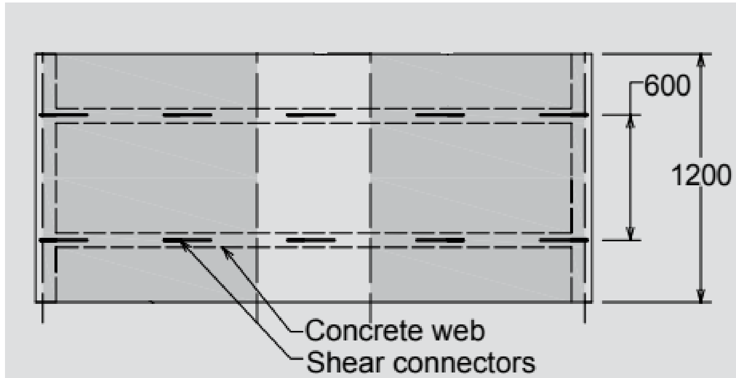


Figure 33: Spacing of shear connectors from (Tomlinson & Fam, 2015).

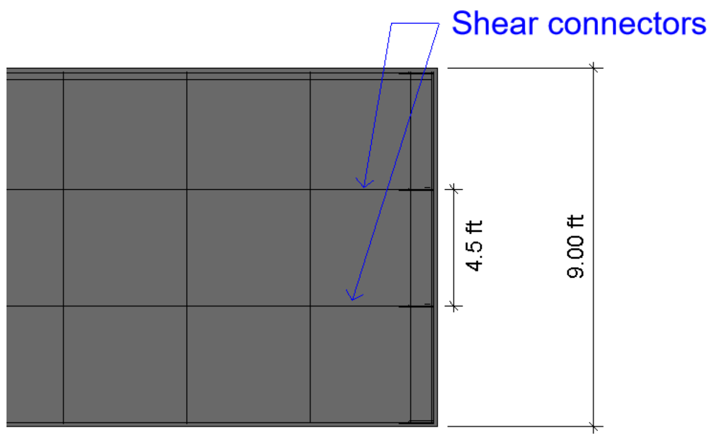


Figure 34: Spacing of shear connectors in this study.

Reinforcement size adaptions and additional specifications described below were applied to the study according to the National Building Code of Canada (NBCC) 9.15.4 "Foundation walls."

- No less than one 15M bar on top of all walls shall be installed.
- At least one 15M bar above and below openings greater than 1.20 meters wide should be installed.
- Minimum rebar size for vertical and transversal reinforcement is 15M
- Dowels shall be included in all horizontal reinforcement

4.5 Cast In Place Slabs

Considering that cast-in-place slabs are typically cast monolithically, the design required incorporating a continuous slab system. Casting the slabs monolithically helps to distribute loads more evenly and prevents differential settlement, which can cause cracks and structural issues. Additionally, it makes concrete casting a practical activity on the site, rather than pouring in many sections. Consequently, four 500mm by 250 mm beams, 7 meters long, were introduced along the shorter span of the slabs, as illustrated in Figure 35. Moreover, Table 3 shows the design criteria for cast-in-place slabs and beams.

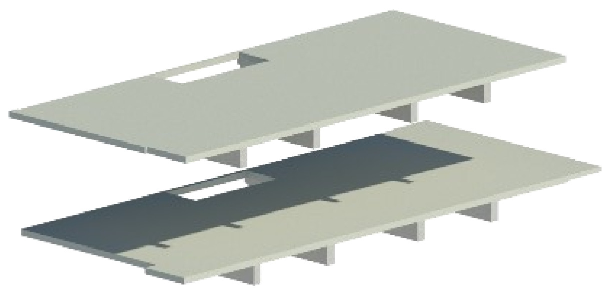


Figure 35: Concrete slabs system.

Table 3. Design criteria for cast-in-place slab system.

Thickness of main slabs	6.5 inches
Thickness of porch slab	2.5 inches
Beam height	500 mm
Beam width	250 mm
Live load	2.39 kPa
Dead load	1kPa
Concrete cover	25 mm
Positive moment reinforcement	15M @ 500 mm
Negative moment reinforcement	15M @ 500 mm

Shrinkage and temperature reinforcement	15M @ 500 mm

4.5.1 Structural analysis and design procedures

4.5.1.1 Beams

The structural design of the four rectangular beams was performed based on design requirements as stipulated in the Canadian Standards Association code (CSA) A23.3-04 “Design of concrete structures”, Canadian Standards Association (2004) and the National Building Code of Canada (NBCC). To meet the ultimate and service limit states, the design accounted for live loads, dead loads, and the self-weight of both the beams and the slab, as well as factored loads and moments. Following this, the necessary area of steel reinforcement, clear cover, and reinforcement spacing were computed.

4.5.1.1.1 Material properties

- Concrete f’c= 35MPa. Since beams are not exposed to the exterior, durability is not a concern; concrete is not exposed to harsh environments based on CSA A23.1—Table 1, which defines four different classes of harsh environmental exposures, such as freezing and thawing conditions, chlorides, silage gases, etc.
- In case the structure is categorized in one of these classes, increments in compressive strength should be applied to improve concrete durability and, thus, performance.
- Reinforcement fy= 400 MPa.

4.5.1.1.2 Dimensions

- Effective height and width dimensions were selected based on deflection and strength requirements.
- The effective height of the beam was determined based on the span-to-depth ratio, which was considered to control deflection, using a ratio of L/16 as stated in Table 9.2 of CSA 9.8.2 “One-way construction” where “L” represents the span length of the beam (7 meters) and 16 is the factor used for simply supported beams.
- The width was selected as ½ of the beam height.

4.5.1.1.3 Load and moment computations

- A volumetric weight of concrete was assumed as $24kN/m^3$ for the structure's computations.
- Factored loads were determined by reviewing the NBCC loading conditions to find the most unfavorable conditions (Scenario in which the structure is most at risk; loading scenarios that are most likely to result in the highest stress or strain on a structure). The first combination assumed 1.4 dead loads; meanwhile, the second combination considered 1.5 live loads and 1.25 dead loads, being the one that governed.
- Factored moment was calculated with the expression " $\frac{wl^2}{8}$ "

4.5.1.1.4 Reinforcement selection

- The required reinforcement area "As" was calculated, resulting in 1076 mm^2. Leading to the selection of three 25M bars.

4.5.1.1.5 Checks for lateral stability and crack control

- Lateral stability consisted of checking if the function L/50 < b, where L = span and b= width of beam. In this case, L/50 successfully complied, resulting in 140mm, being less than b (250mm)
- Crack control was performed based on 10.6 "Beams and one-way slabs - Crack control" of CSA 23.3.

4.5.1.2 Slabs

On the other hand, the structural design of concrete slabs was conducted using the Approximate Frame Analysis method. This method allows for a simplified analysis of continuous supports for one-way slabs and provides a practical approach for determining the slabs' structural behavior and requirements.

The design adhered to the Canadian Standards Association (CSA) A.23.3-04 "Design of Concrete Structures" and the National Building Code of Canada (NBCC), focusing on criteria for deflection and strength. On the other hand, live and super-imposed dead loads were obtained from the original project at 3i PC, along with the self-weight of the elements designed.

4.5.1.2.1 Material properties

- Concrete f'c= 35MPa. Since slabs are not exposed to the exterior, durability is not a concern; concrete is not exposed to harsh environments based on CSA A23.1—Table 1, which defines four different classes of harsh environmental exposures, such as freezing and thawing conditions, chlorides, silage gases, etc.
- In case the structure is categorized in one of these classes, increments in compressive strength should be applied to improve concrete durability and, thus, performance.
- Reinforcement fy= 400 MPa.

4.5.1.2.2 Slab thickness

- Slab thickness was determined using a ratio of L/20 for one-end continuous supported slabs, L/28 for both end continuous slabs and L/20 for simply supported slabs as stated in Table 9.2 of CSA 9.8.2 "One-way construction." Where "L" represents the span length of the slab and 20 and 28 are the factors used depending on the supporting conditions.
- Due to the different variations in span length, slab thickness was chosen based on the most critical scenario.
- 6.5 inches was chosen as the adequate thickness of the two slab systems (main floor and second floor).
- An additional 2.5-inch thick concrete slab, measuring 23.5 ft by 4.1 ft, as depicted in red in Figure 36, has been independently designed for the porch. This slab is simply supported, with one side resting on the main floor wall and the other supported by two columns.

4.5.1.2.3 Design of moments and shears

- Factored loads were determined by reviewing the NBCC loading conditions to find the most unfavorable conditions. The first combination assumed 1.4 dead loads; meanwhile, the second combination considered 1.5 live loads and 1.25 dead loads, being the one that governed.

- The approximate frame analysis method was employed to determine moments and shears. This method simplifies the design process for frames with two or more spans by providing straightforward and standard formulas for computations (See Figure 37).

4.5.1.2.4 Concrete Cover and Cut-off Locations

- Concrete cover was chosen as 25 mm for top and bottom bars as indicated in Table 17 "Concrete cover," CSA A23.1.
- Top reinforcement at exterior supports is obtained by dividing the exterior span by 4; meanwhile, the one at interior supports results from the span divided by 3. Figure 38 illustrates the cut-off location details.

4.5.1.2.5 Shrinkage and Temperature Reinforcement

- The minimum reinforcement was calculated based on 7.8.1 "Minimum reinforcement in slabs" and maximum bar spacing on 7.4.1.2 "Spacing and reinforcement of tendons" in CSA A23.1.

4.5.1.2.6 Strength Requirements

- Positive and negative reinforcement in the interior and exterior spans were defined with the formula As= Mr/0.92øsfyd, where "As" is the required reinforcement, "Mr" is the maximum factored moment, "Øs" refers to the security factor (0.85), "fy" is the reinforcement fluency, and "d" is the reinforcement depth.
- Steel bar sizes and spacing were selected based on the required reinforcement area ("As") for maximum positive and negative moments. Subsequently, this selection was verified to ensure the bars' actual resistant moment met the required strength requirements.
- Figure 39 depicts rebar modeled in both main and second floor slabs highlighted in red.
- Crack control was performed based on 10.6 "Beams and one-way slabs - Crack control" of CSA 23.3.
- The shear resistance of the slab was checked based on 11.3.3 "Factored shear resistance" stated in CSA 23.3.

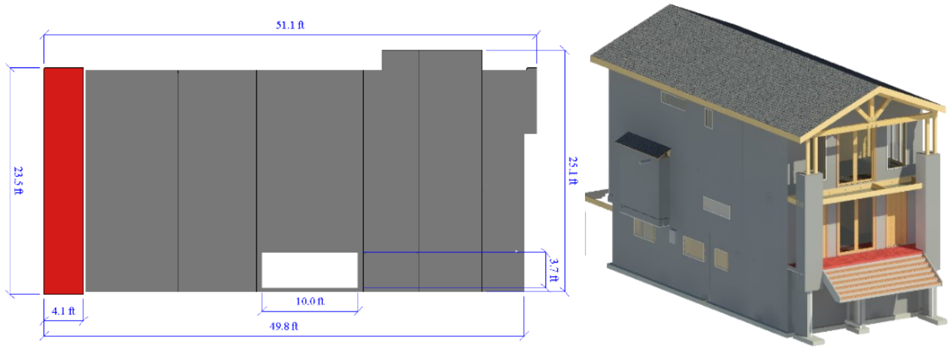


Figure 36: Porch slab.

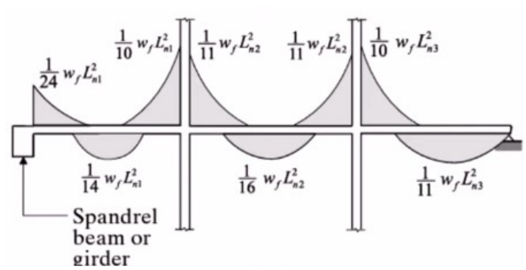


Figure 37: Approximate Frame Analysis equation graph.

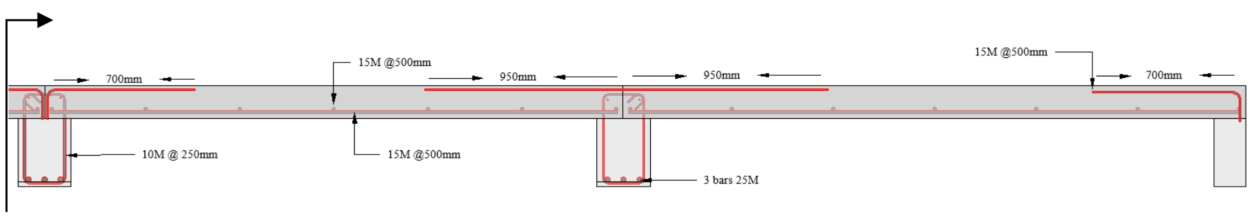


Figure 38: Slab cutoffs and beam details.

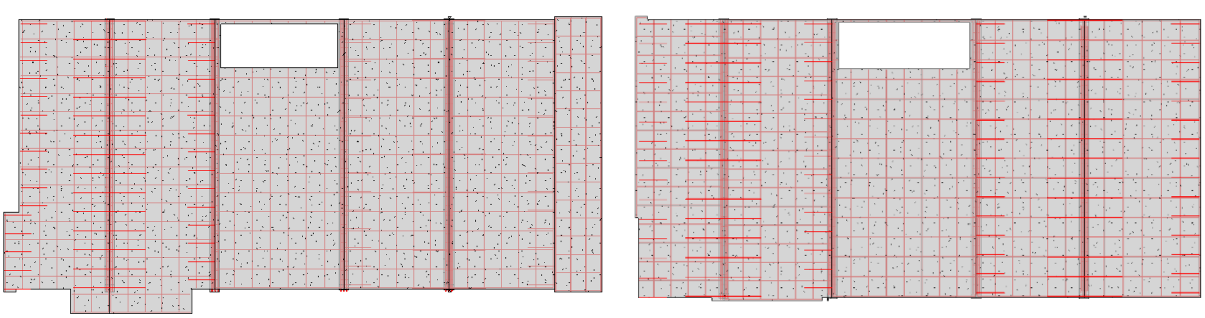


Figure 39:Main and second-floor cast-in-place slabs rebar details.

4.6 Hollow-core slabs

The hollow-core slabs were designed using spreadsheets and the design manual “Manual de diseño de estructuras prefabricadas y presforzadas”, Eduardo Reynoso et al. (2000) provided by a reputable firm specializing in precast concrete solutions. Both resources base their structural design principles on the international code ACI 318-19 “Building Code Requirements for Structural Concrete and Commentary", American Concrete Institute (2022) ensuring safety and performance requirements compliance.

The spreadsheets considered various input parameters related to the slabs, such as span, live loads, dead loads, slab thickness (15, 25, or 30 cm), and the number of tendons (3, 4, 5, or 6), as both plank thickness and the number of tendons are standardized. Additional inputs included the concrete's compressive strength, as well as the spacing and size of the reinforcing steel used in the composite layer of reinforced concrete, which is cast on top of the planks to integrate them.

Upon entering these inputs into the spreadsheets, they generated outputs that determined whether the slab design met the required standards, codes, and design manuals in terms of structural requirements such as load-bearing capacity and resistance of moments. This process ensured that each hollow core slab design was compliant with industry regulations and capable of performing effectively under the specified conditions.

These spreadsheets provided a streamlined and efficient method for assessing the structural integrity and compliance of hollow-core slab designs, facilitating the overall design process.

Further, the 3D modeling of hollow-core slabs involved creating a “family” in Adobe Revit to customize details of planks such as width, height, number of voids, void size, and rib dimensions between voids. The final design of both slabs is depicted in Figure 40.

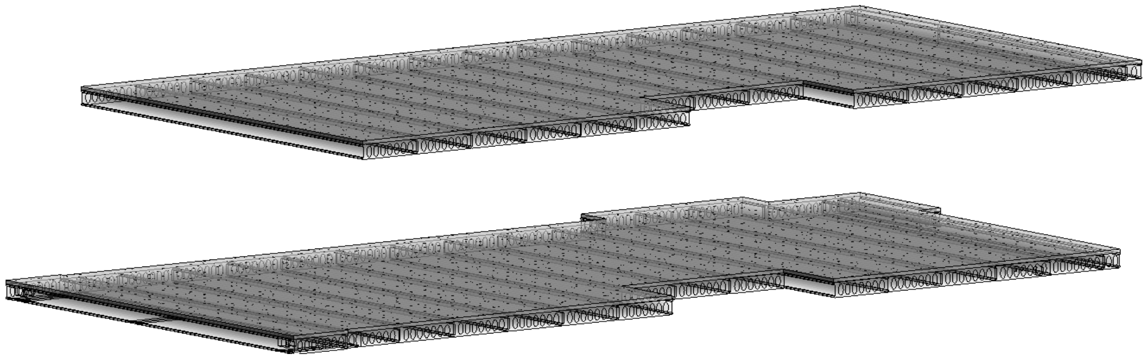


Figure 40: Hollow-core slabs system.

4.6.1 Data collection

- Permanent and variable loads supported by the slabs, including self-weight, finishes, and usage loads, were identified.
- Spans and support conditions were identified to calculate the minimum thickness of Hollow-core planks.
- Slab span and support conditions were 7 meters and simply supported.

4.6.2 Design procedure

- Spreadsheets were used to validate the thickness previously proposed, determine the thickness of the solid concrete layer on top of the planks, and determine the total depth of the system.
- Various inputs, such as the concrete compressive strength and type of structure (residential), were considered to determine load combination factors used for factored load computations.
- Additional parameters of the structure's live, dead, and self-weight loads were input.
- Calculation sheets were used to check for compliance with the number of prestressed strands, reinforcement size, and wire mesh spacing for negative moments, which were chosen based on common standards.
- The final design for both slabs consisted of 30 hollow-core planks in total, each 1 meter wide and 25 cm thick, with 3 prestressed strands of 9.5mm diameter.

- A 6 cm thick solid concrete slab on top with a 6x6 6-6 reinforcement grid gave the most optimized design based on loads, maximum span, concrete compressive strength, and reinforcement proposed. Figure 41 illustrates design details.

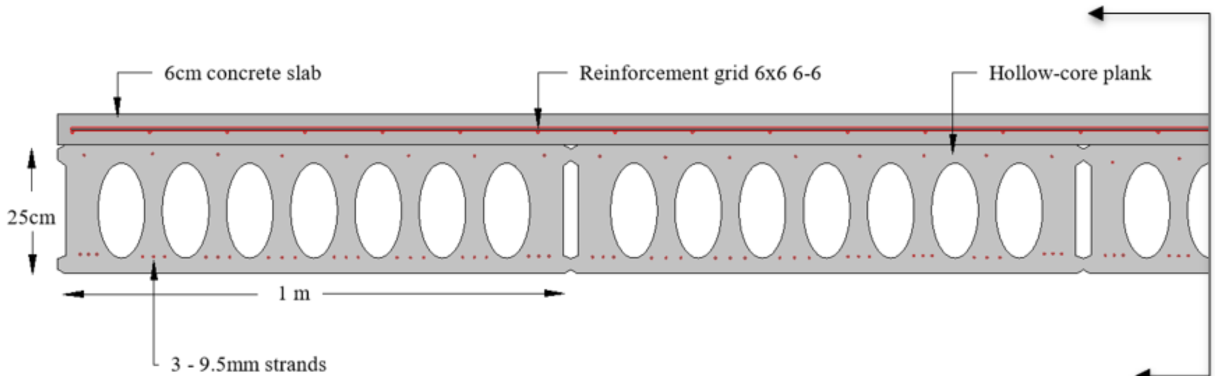


Figure 41:Hollow-core slab design details.

4.6.3 Adaptations to Canadian Common Practice

Spreadsheets consider prestressed reinforcement wire of 5mm diameter for the concrete planks. Typically, in countries such as Canada, the United States, and some parts of Europe, hollow-core slab reinforcement consists of prestressed strands with a minimum diameter of 9.5 mm. Consequently, the type and size of prestressed reinforcement were changed to adapt the design to Canadian industry standards.

4.7 Design of formwork

Structures that require formwork**,** such as Insulating Concrete Form walls, concrete sandwich wall panels, cast-in-place slabs, and hollow-core slabs, were designed according to Chapter 10, "Concrete Structures," Part 1, "Forms"," from the book "*Estimating Construction Costs"* by Peurifoy & Oberlender (2014). Additionally, material takeoff was calculated to analyze the significance of formwork's carbon emissions introduced to each construction practice.

Specifically, hollow-core planks do not require formwork since their construction is based on concrete extrusion (see Figure 42). However, the formwork considered for this method was due to the cast-in-place concrete layer on top, which serves to unify planks and enhance structural integrity and does require formwork to ensure proper shaping and curing. The design for this slab, illustrated in Figure 43, includes 3/4 in thick plywood sheets placed on the hollow-core planks, which support the load of the concrete slab, eliminating the need for shoring and bracing. Additionally, 2x6 dimensional lumber is placed vertically and horizontally on all sides on top of the wall, where concrete is cast and connected by metal hinges to support and prevent bending and collapse of the formwork.

On the other hand, ribbed walls and ribbed slabs are cast on the ground level using insulation as formwork. This approach eliminates the need for traditional formwork, making these elements effectively formwork-free while providing dual functionality to the insulation, serving both structural and thermal purposes.

Similarly, the Insulating Concrete Form method does not eliminate formwork entirely; it uses ICF blocks as a permanent formwork to shape the walls. However, bracing is required to support loads and stabilize the Styrofoam blocks during the concrete pouring and curing process. Timber studs of 2x4 were used as strongbacks and anchor foots to support and stabilize the walls, as shown in Figure 44. Anchor foots were placed at one-third of the wall height (6.75 ft) at an inclination of 12.73 ft at a 45-degree angle.

Conversely, sandwich panels are cast offsite at ground level, eliminating the need for shoring and bracing during installation, as shown in Figure 45. The design includes ¾ in thick plywood placed on the floor, which ensures a fine finish and separates the concrete from the floor, preventing moisture and imperfections in the concrete. Additionally, vertical and horizontal dimensional lumber of 2x12, tied together by metal hinges, was used to provide structural support and maintain the shape of the panels during curing.

Finally, the formwork for cast-in-place slabs, depicted in Figure 46, consisted of 4x4 joists spaced 20 inches in the center, ¾ in thick plywood, 4x6 stringers spaced 48 inches in the center, and shores for support. The quantity of material used depends on the thickness of the slab and its height above the supporting floor. The design followed the guidelines in Table 10.4 of "Estimating Construction Costs" by Robert Peurifoy and Garold Oberlander, which provides a practical approach to computing material quantities for cast-in-place concrete slabs.

Figure 42: Extrusion of hollow-core planks (Dezhou Haitian Electromechanical Technology, 2013).

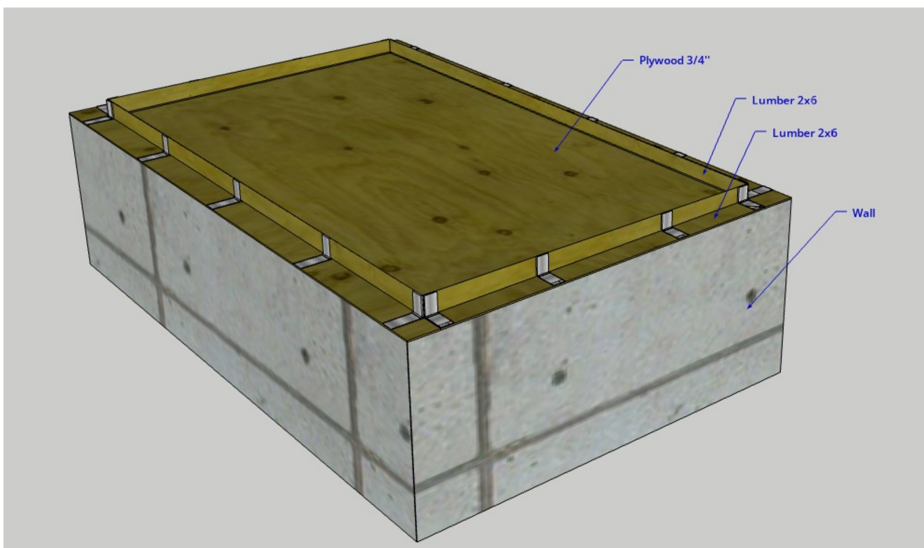


Figure 43:hollow-core slab formwork.

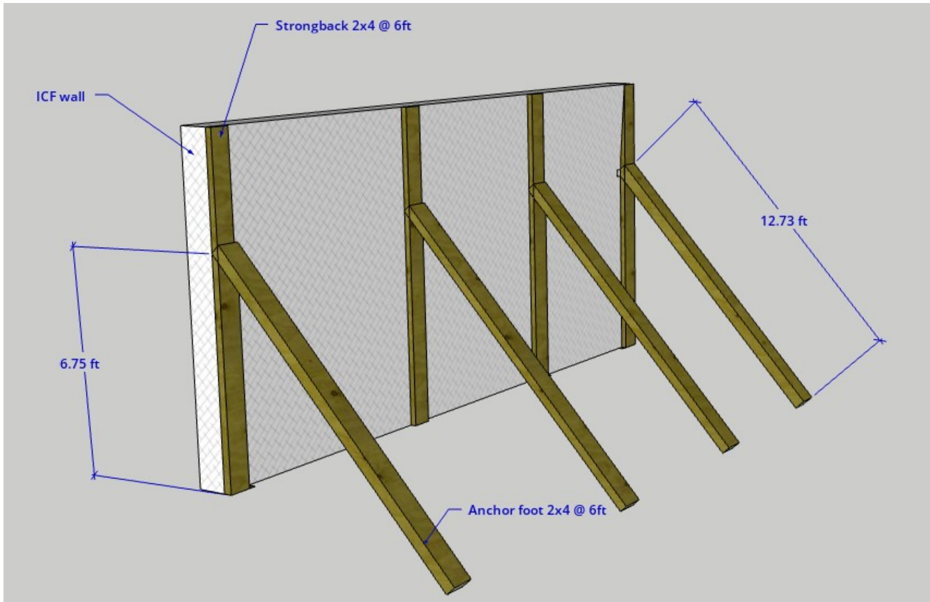


Figure 44: ICF bracing.

Figure 45: Concrete Sandwich panel formwork.

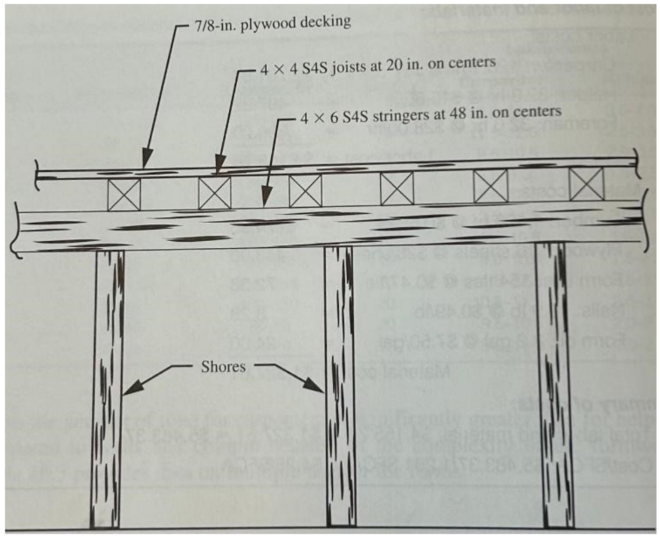


Figure 46: Cast-in-place slabs formwork (Peurifoy & Oberlender, 2014).

4.8 Extraction of material takeoff REVIT

Material consumption is the main factor contributing to embodied carbon in construction, specifically in the material manufacturing stage. Therefore, analyzing the extraction of material volumes is essential, allowing the identification of material usage and assessing direct environmental impact. Autodesk Revit is a widely used Building Information modeling tool in the industry that offers advanced features for creating material takeoffs from 3D models.

Material volumes were obtained from the structural design and modeling of the structures in Revit. These volumes were then used for the embodied carbon assessment. For the evaluation, volumes were converted to weight in kilograms.

When designing the basement walls, materials such as concrete, formwork timber, reinforcement steel, and insulation were considered. However, insulation was not included for slabs. Internal floors typically do not require thermal insulation to the same extent as walls. The decision to include insulation in the slabs will depend on the client's preference and specific project requirements. As a result, the analysis only focuses on concrete, reinforcement and formwork material for the slabs.

Figures 47 and 48 illustrate a takeoff schedule generated in Revit, showing different details and specifications that facilitate data analysis.

<FLAT SLAB 2- Rebar Schedule>

A	B	C	D	E
Label	Type	Bar Diameter	Reinforcement Volu	WEIGHT
FLAT SLAB 2	10M	3/8"	22241.14 cm³	174.59 kg
FLAT SLAB 2	15M	5/8"	89286.49 cm³	700.90 kg
FLAT SLAB 2	25M	1"	41323.54 cm³	324.39 kg
			152851.17 cm³	1199.88 kg

Figure 47: Rebar Schedule extracted from Adobe Revit.

<FLAT SLAB 2 CONCRETE SCHEDULE>

A	B	C	D
Label	Structural Material	Volume	weight
FLAT SLAB 2	Concrete, Cast-in-Pla	15.87 m³	38096.96 kg
		15.87 m³	38096.96 kg

Figure 48: Concrete Schedule extracted from Adobe Revit.

4.9 Cost of material

The cost of materials in Table 4 was determined by averaging prices obtained from ten different suppliers in various Edmonton, Alberta regions. This approach ensured a comprehensive and representative cost estimation, accounting for regional price variations and providing a more accurate financial assessment for the study.

Table 4. Material costs

Material	Unit	Cost (CAD)
Concrete 35MPa	Cubic meter	271
Concrete 40MPa	Cubic meter	320
Rebar 10M	Feet	0.42
Rebar 15M	Feet	0.98
Rebar 25M	Feet	2.37
Strand 9.5mm	Feet	0.304
Wire mesh 6x6 6-6	Squared feet	0.57
Wire mesh 10x10 10-10	Squared feet	0.37

Insulation 2 in thick	Squared feet	2.04
Insulation for ribbed elements	M3	0.40
ICF blocks	Piece	30.31
Plywood ¾’’	Squared feet	37.48
Formwork studs 2x4	Cubic meter	380.12

The total structure cost from each construction method was calculated by multiplying the volume of each material by its respective cost.

4.10 Carbon footprint analysis and embodied carbon factors.

As illustrated in Figure 49, this study's carbon emissions assessment encompasses two stages of the building life cycle analysis: the product manufacturing stage (A1-A3) and a portion of the construction process stage (A4 and A5w). These stages represent over half of LCA's carbon emissions (55%), and the vast majority of embodied carbon when analyzing preliminary designs, making carbon emissions more accurately predictable and facilitating the identification of room for mitigation in stages and substages in the project design phase.

A1-A3 consists of the extraction, processing, transportation, and manufacture of materials and products until they leave the factory gate to be taken to the site. Moreover, A4 represents the transportation of materials and products from the manufacturing factory to the gate to the site. Stage A5, conversely, is divided into two substages: A5a, which represents construction operations, and A5w, the material waste.

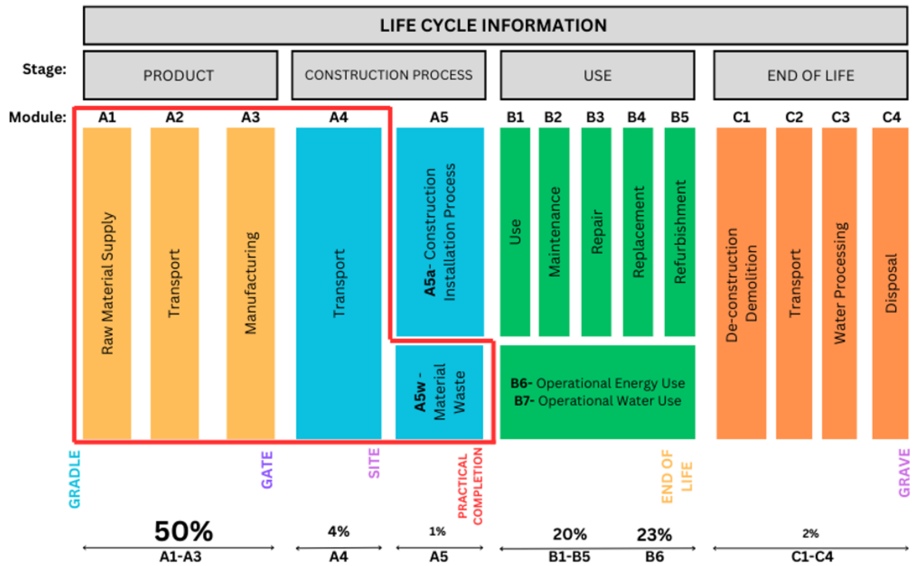


Figure 49: Life cycle stages and modules (John Orr et al., 2020).

On the other hand, Life cycle modules in onsite and offsite operations differ. When analyzing the offsite construction operations, an additional substage is identified, consisting of the transportation of structures from the precast factory to the installation site (Figures 50 and 51).
For the purpose of this study, this additional substage is named "A4b" and is incorporated into the analysis since it contributes to the embodied carbon for those offsite construction methods included in this comparison.

Similarly, the "A4c" substage is incorporated into this study to account for transporting formwork timber materials to the storage facility. Moreover, Tables 5, 6, and 7 illustrate embodied carbon factors for each building material and transportation scenario, as well as percentages of material waste used for this assessment.

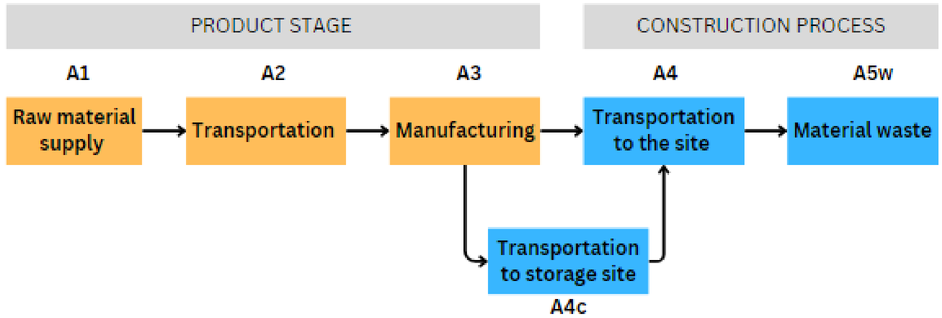


Figure 50: Onsite construction operations.

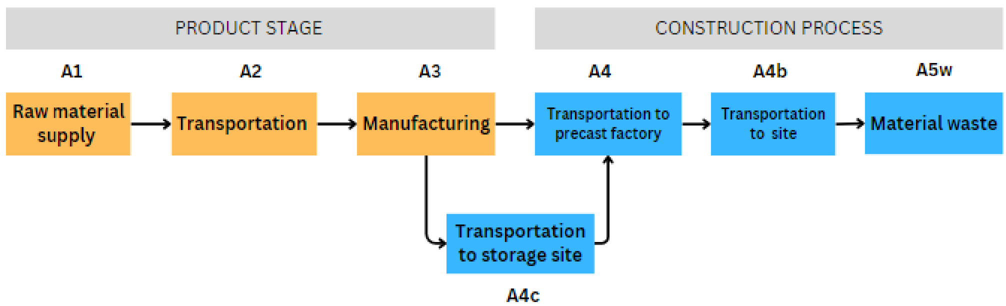


Figure 51: Offsite construction operations

Table 5. Embodied carbon factors in activities A1-A3

Material	kg CO_2 eq/kg	References
Concrete 35 MPa GU with air (Cast in place)	0.157	(Canadian Ready-mixed Concrete Association, 2022)
Concrete 35 MPa SCC (Precast)	0.1572	(Canadian Ready-mixed Concrete Association, 2022)
Concrete 40 MPa SCC (exclusively for ribbed structures)	0.1772	(Canadian Ready-mixed Concrete Association, 2022)
Insulation EPS	4.205	(Jones & Hammond, 2019) ICE V3

Reinforcement steel / PT strands	1.99	(Jones & Hammond, 2019) ICE V3
Formwork timber	0.681	(Jones & Hammond, 2019)ICE V3

Table 6. A4/A4b/A4c embodied carbon for typical transport scenarios. (John Orr et al., 2020)

Stage-transport scenario	km traveled by road	ECF ($kgCO_2$ e/kg)
A4b/A4c - Locally transported	50	0.005
A4- Nationally transported	300	0.032

Table 7. Waste factors for typical structural materials (John Orr et al., 2020)

Material	Waste rate
Concrete in situ	5%
Precast concrete	1%
Reinforcement steel	5%
Insulation EPS	5%
Formwork timber	5%

Computations performed after the material take-off extraction consisted of the following:

Emissions from the materials manufacturing stage (A1-A3) computations, as shown in equation 1, result from the product of each material quantity in kilograms and its embodied carbon factor (ECF) from the manufacturing stage, as indicated in Table 5.

$$\textit{A1-A3 emissions} = \textit{Material volume (kg)} * \textit{ECF} \qquad (1)$$

Equation 2 calculates the carbon emissions from each material's transportation from the manufacturing facility to the site stage (A4). This is by multiplying the material quantity in kilograms by the corresponding factor in Table 6. Due to the wide variety of manufacturers around Canada, the transportation is considered nationally manufactured (300km).
Similarly, A4b carbon emissions are computed following the same logic as A4. This stage represents the transportation of the same building materials assembled as panels (wall or slab panels). On the contrary, the embodied carbon factor in this stage is considered locally manufactured, assuming that precast panels are transported at a maximum distance of 50 km.

$$\text{A4 emissions} = \text{Material volume (kg)} * ECF \qquad (2)$$

When calculating the embodied carbon associated with transporting materials from the storage facility to the site and vice versa, materials were assumed to be locally transported. To calculate this, the quantity of material in kilograms was multiplied by its corresponding CO_2 factor from Table 6 and then scaled by the number of times the materials were transported, as shown in Equation 3.

$$\text{A4c emissions} = \text{Material volume (kg)} * ECF * 2 \qquad (3)$$

The material waste (A5w) carbon emissions of each building material are derived from the product of the material waste factor (Wf) in Table 7 and the sum of the manufacturing and transportation embodied stages factor. As shown in Equation 4, having determined the factor, it is multiplied by the material quantity.

$$A5w = [Wf \times (A1\text{-}A3 + A4)] * \text{Material volume (kg)} \qquad (4)$$

4.10.1 Embodied carbon phases considered for each construction method.

The computations of total embodied carbon for each construction method consisted of the elaboration of spreadsheets to facilitate the assessment. Results were obtained by summing results from equations 1, 2, 3, and 4, depending on the phases considered for each construction method. As shown in Table 8, certain stages in the assessment are specific to particular construction methods. For instance, transportation stage A4b is relevant only to off-site construction methods, as it accounts for the additional transport of materials from the offsite facility to the construction site. Similarly, A4c pertains exclusively to methods that necessitate the transportation of formwork timber materials between the storage facility and the site.

Table 8. Stages comprehended by construction practice.

Construction method	Manufacturing of materials (A1-A3)	Transportation of materials from the manufacturer to the site (A4)	Transportation of materials from the offsite facility to the site (A4b)	Transportation of materials subjected to storage(A4c)	Material waste (A5w)
Insulating Concrete Form walls	✓	✓		✓	✓
Concrete Sandwich walls	✓	✓	✓	✓	✓
Ribbed walls	✓	✓	✓		✓
Cast-in-place slabs	✓	✓		✓	✓
Hollow core slabs	✓	✓	✓	✓	✓
Ribbed slabs	✓	✓	✓		✓

Figure 52 illustrates an example of embodied carbon computation for concrete sandwich panels. Inputs included the quantity of materials in kilograms extracted from the 3D REVIT model, material waste factor percentages, and embodied carbon factors (ECF). Outputs were generated based on Equations 1 through 4 for each building material. The green square in

Figure 52 provides detailed embodied carbon results at each stage and for each material. Additionally, the total carbon emissions by material are calculated and summarized.

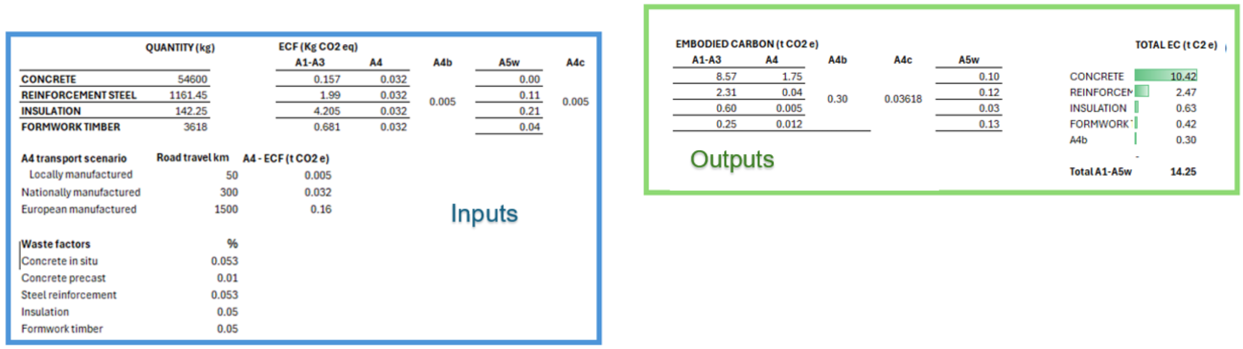


Figure 52: Computations of concrete sandwich panels developed in spreadsheets

For this example, computations were performed for the LCA stages applicable to concrete sandwich panels. As illustrated in Table 8, only the embodied carbon stages relevant to the construction method are considered, and these stages vary depending on the building practice.

CHAPTER 5: RESULTS

This chapter presents detailed results of the assessed construction practices through charts illustrating the embodied carbon contribution by building materials and detailed emissions at each stage of the Life Cycle Analysis (LCA). Additionally, it provides total costs and a breakdown of expense percentages by construction materials.

Finally, this chapter provides overall comparisons of material consumption, carbon emissions, and costs of all construction methods. These comparisons are divided into basement walls and concrete slabs to give better insights into each construction type's specific impacts and efficiencies.

5.1 Basement Walls

5.1.1 Insulating Concrete Form Walls

The carbon emissions and materials costs were analyzed based on computations in chapters 4.9, "Cost of materials," and 4.10, "Carbon footprint analysis and embodied carbon factors". Table 9 illustrates the material quantities of Insulating Concrete walls extracted from the 3D REVIT model.

Table 9. ICF Material consumption

Material	Quantity (kg)
Concrete	55,464
Reinforcement steel	957.86
Insulation	397.25
Formwork timber	828

5.1.1.1 Carbon emissions

Figure 53 compares the embodied carbon impact of each construction material used to build basement walls using the Insulating Concrete Form (ICF) method.

The total carbon emissions were recorded as 14.94 tons of CO_2e. Concrete emerged as the most significant contributor to environmental harm, accounting for 73.87% of the total emissions. Reinforcement steel followed, contributing 13.65%, approximately 60% less than the emissions from concrete.

Moreover, insulation materials represent 11.83% of the total emissions, just below reinforcement steel by around a quarter of a ton of carbon footprint (2%).
In contrast, using formwork and bracing for ICF walls was minimal. Because most formwork was eliminated, bracing contributed only 0.1 tons of CO_2e of embodied carbon, representing a mere 0.65% of the overall emissions in constructing the basement walls.

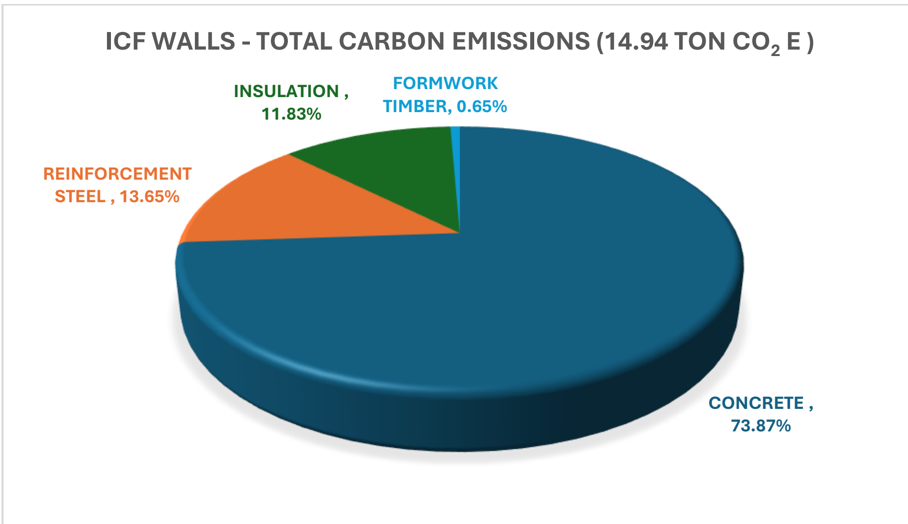


Figure 53: Insulating Concrete Form walls carbon emissions by material.

Figure 54 highlights the carbon footprint at each stage of the construction processes analyzed in this research, detailing the contributions of different construction materials. Notably, the stages involving material extraction, transportation to the manufacturer, and the manufacturing process (A1-A3) produce the highest CO2 emissions, totaling 12.35 tons of CO_2e.

Conversely, emissions from material waste have the least impact, amounting to just 0.77 tons of CO_2e. Emissions from transportation (A4), specifically the transport of materials from the manufacturer to the construction site, are higher, registering at 1.82 tons of CO_2e. This is about 57.69% more than the emissions from material waste but significantly less than those from the A1-A3 stages by over 85%.

A clear trend emerges in terms of emissions by construction stage, with concrete having the most substantial environmental impact, followed by reinforcement steel, insulation, and formwork timber.

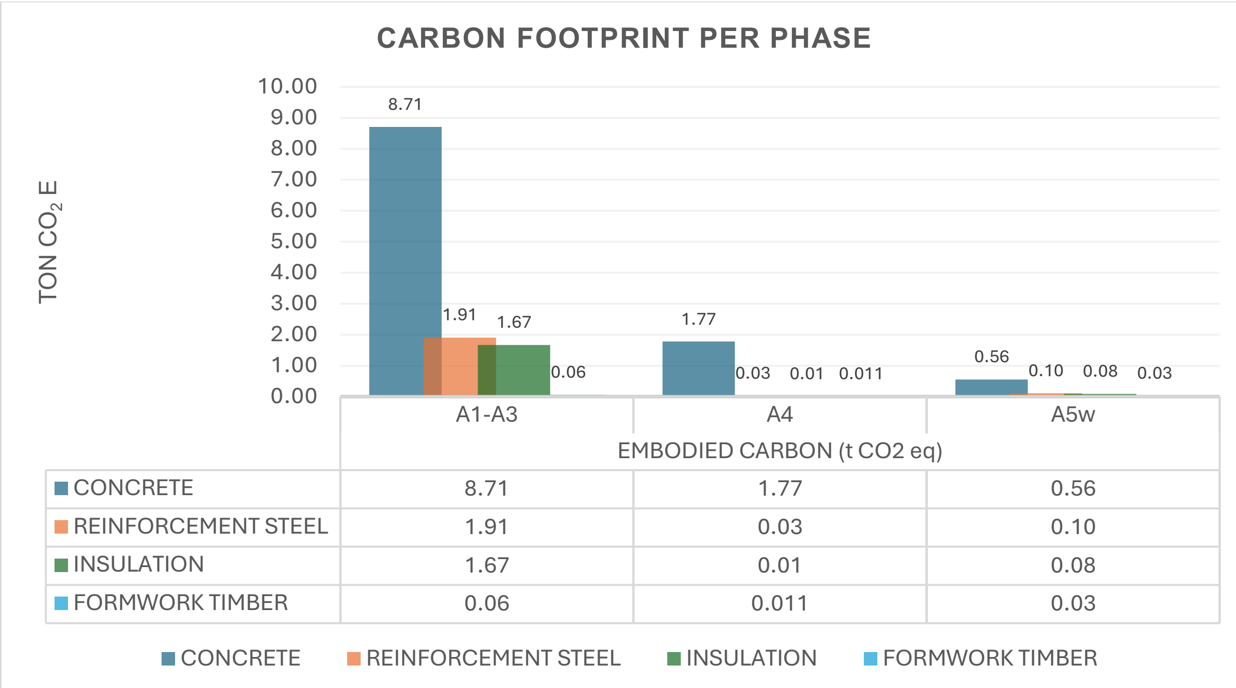


Figure 54: Insulating Concrete Form walls carbon emissions by stage

5.1.1.2 Costs of Material

Figure 55 presents the total material cost for the Insulating Concrete Form (ICF) construction method based on Table 10, along with a percentage breakdown by material. Surprisingly, insulation is the most expensive material, totaling $7,092.54, contrary to typical expectations, where concrete is usually the most expensive material, followed by reinforcement. The explanation is the high cost of insulating forms used for this construction practice. These blocks are built by two layers of insulation that work as forms to cast concrete, allowing for the partial elimination of formwork in the system as described in chapter 3.1.1, "Insulating Concrete Form Walls". The cost for one ICF block of 48 inches long by 8 inches height can cost up to CAD 30.31. In this case, this construction method used 234 pieces.

On the other hand, concrete is the second most costly material, just 5% less than insulation, with a total cost of $6,262.81, followed by $1829.52 of reinforcement steel (12%).

Formwork timber, 9% less expensive than reinforcement steel, accounts for a modest 3% of the total costs ($524.57), reflecting the minimal use of bracing material compared to the rest of the formwork system.

Table 10. ICF cost of materials

Material	Quantity	Units	Unit cost	Total cost
Concrete 35 Mpa	23.11	m3	$ 271.00	$ 6,262.81
Rebar 10M	1859.44	ft	$ 0.42	$ 780.77
Rear 15M	1063.60	ft	$ 0.99	$ 1,048.75
Insulation blocks	234	Pc	$ 30.31	$ 7,092.54
Formwork timber	1.38	m3	$ 380.12	$ 524.57
			Grand Total	**$15,709.44**

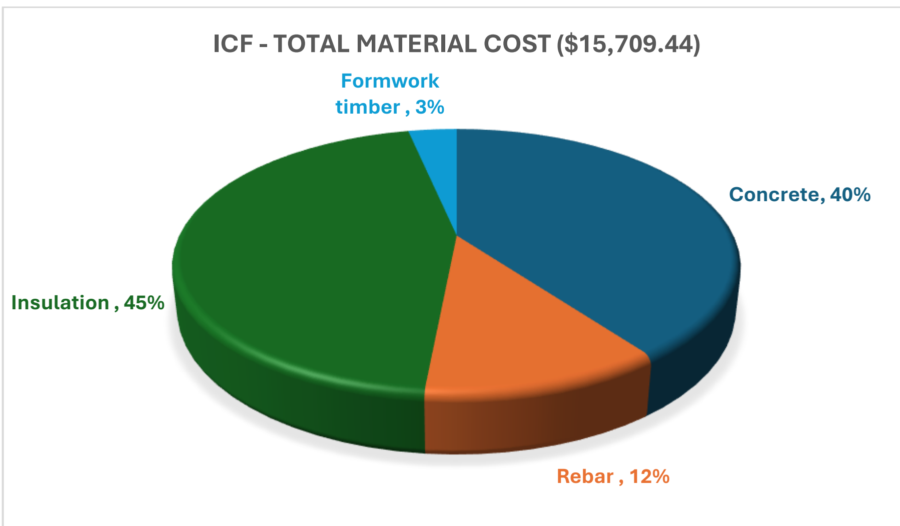


Figure 55. Overall Cost and Material Percentage Breakdown of Insulating Concrete Walls

5.1.2 Concrete Sandwich Panels

The analysis of carbon emissions and material costs are based on calculations detailed in Chapters 4.9, "Cost of Materials," and 4.10, "Carbon Footprint Analysis and Embodied Carbon Factors." Table 11 presents the quantities of materials used for Concrete sandwich panels, as extracted from the 3D REVIT model.

Table 11. Concrete sandwich panels material consumption

Material	**Quantity (kg)**
Concrete	54,600
Reinforcement steel	1,161.45
Insulation	142.25
Formwork timber	3,618

5.1.2.1 Carbon emissions

As depicted in Figure 56, total emissions from concrete sandwich panels are mainly caused by the use of concrete and reinforcement steel. These materials together account for approximately 12.8 tons of CO_2e emissions, with concrete contributing 73.15% and reinforcement steel 17.35%.

On the other hand, emissions from insulation materials (4.44%) and timber used for formwork (2.97%) are the least impactful materials when constructing sandwich panels, representing only 1.05 tons of embodied carbon.

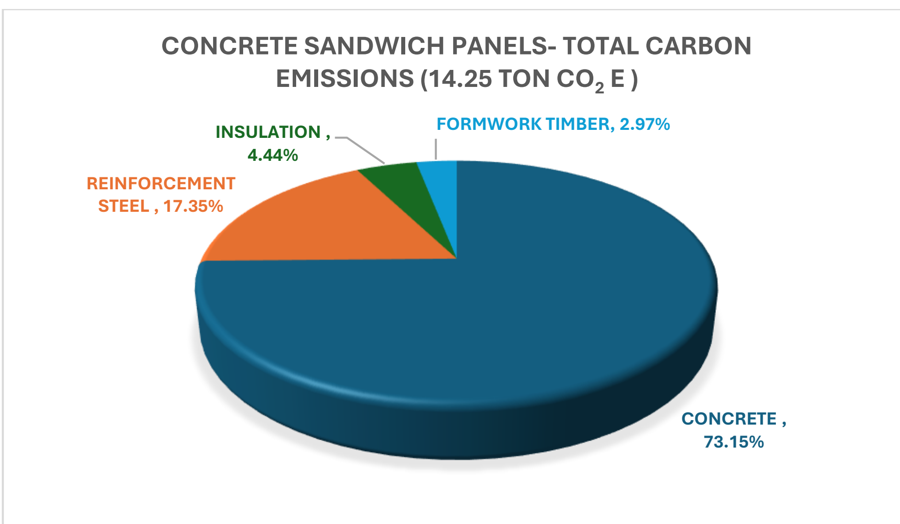


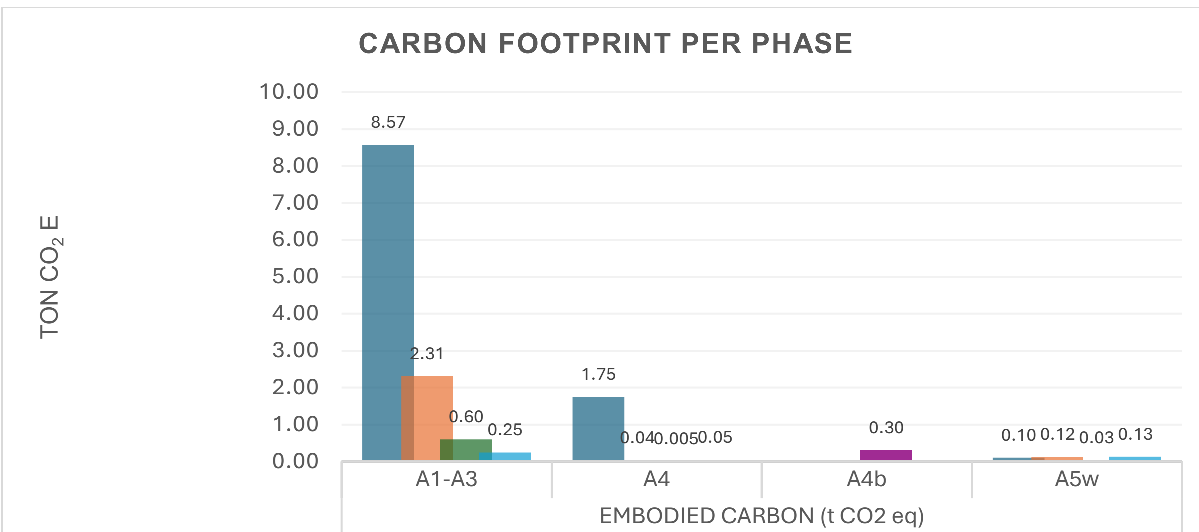
Figure 56: Concrete sandwich panels carbon emissions by material

Figure 57 illustrates the embodied carbon stages of the sandwich panel construction process. A breakdown analysis is performed to analyze the environmental impact of each material at each phase.

11.73 tons of CO_2e carbon emissions were recorded only in the manufacturing stage (A1-A3), comprising 82% of the total, where concrete and reinforcement insulation had the greatest impacts, as previously mentioned in Figure 56.

Moreover, similarly to ICF practices, the transportation of materials is the second largest carbon emitter, followed by material waste, accounting for 1.845 (13%) and 0.38 of CO_2e (2.6%) of embodied carbon.

The additional transportation incorporated by offsite practices (A4b), shown in purple, accounts for the remaining 2.4%. This includes transporting precast elements from the offsite facility to the installation site, adding 0.30 tons of CO_2e emissions. This stage is slightly behind material waste emissions by 2%.



	A1-A3	A4	A4b	A5w
CONCRETE	8.57	1.75		0.10
REINFORCEMENT STEEL	2.31	0.04		0.12
INSULATION	0.60	0.005	0.30	0.03
FORMWORK TIMBER	0.25	0.05		0.13

Figure 57. Concrete sandwich panels carbon emissions by stage

5.1.2.2 Costs of Material

The total material costs for the concrete sandwich panels amounted to $11,691.81, as detailed in Figure 58 and Table 12. Concrete consistently remains the most significant expense, constituting nearly 53% of the total costs, with a substantial $6,165.25. This is followed by the expenditures on formwork timber and reinforcement steel, accounting for smaller yet notable portions of the costs. Formwork timber represents approximately 25% of the overall costs, while reinforcement steel contributes around 20%.

This trend confirms the significant cost implications of formwork material. Although concrete sandwich panels, as an offsite construction method, partially eliminate the use of formwork timber by casting wall panels at ground level without the need for bracing, the material still contributes substantially to the overall costs of these precast reinforced concrete structures. This indicates the broader industry challenge where the expenses associated with formwork remain notable despite the efficiencies gained through offsite methods.

On the other hand, the cost of insulation materials is comparatively minimal, accounting for barely 2% of the total material costs. This amounts to a modest $228, making insulation the least expensive component in the overall material cost distribution for the concrete sandwich panels.

Table 12. Concrete sandwich panels costs

Material	Quantity	Units	Unit cost	Total cost
Concrete 35MPa	22.75	m3	$271.00	$6,165.25
Rebar 10M	399.00	ft	$ 0.42	$ 167.54
Rebar 15M	2215.00	ft	$ 0.99	$2,184.07
Insulation	111.981	sqft	$ 2.04	$ 228.01
Formwork timber	3.71	m3	$380.12	$1,410.26
Formwork plywood	41	sheet	$ 37.48	$1,536.68
			Grand Total	**$11,691.81**

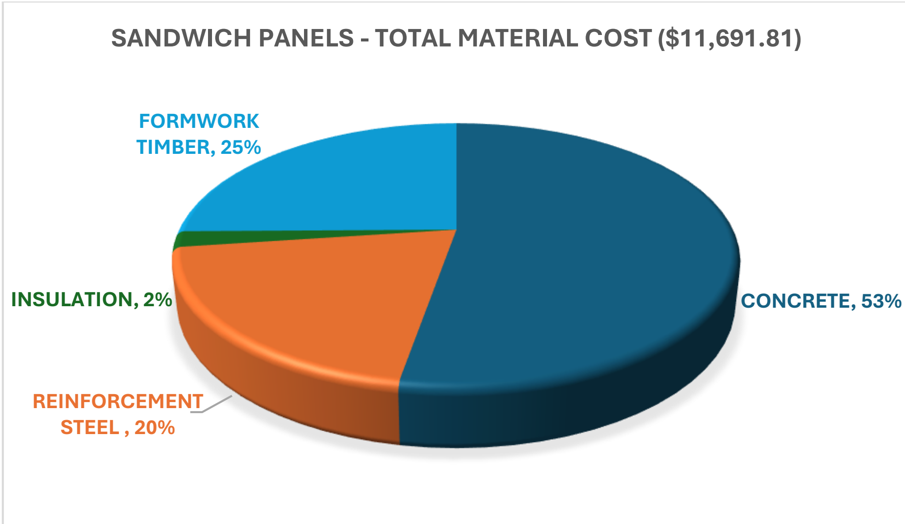


Figure 58: Overall Cost and Material Percentage Breakdown of concrete sandwich Panels

5.1.3 Ribbed Wall Panels

Carbon emissions and material costs are computed from Chapters 4.9, "Cost of Materials," and 4.10, "Carbon Footprint Analysis and Embodied Carbon Factors." Table 13 displays the material quantities for ribbed walls obtained from the 3D REVIT model.

Table 13. Ribbed walls material consumption

Material	**Quantity (kg)**
Concrete	25,047
Reinforcement steel	645.86
Insulation	159.00

5.1.3.1 Carbon emissions

The materials used in constructing ribbed wall panels produce a total carbon emission of 7.37 tons of CO2e. Figure 59 depicts that most of these emissions originate from concrete, responsible for 5.29 tons of CO_2e, or 71.76%, of the total emissions. This figure places concrete significantly ahead of the next major contributor, reinforcement steel, by more than 45%. Reinforcement steel, the second-largest source of emissions, accounts for 1.38 tons of CO_2e, representing 18.65% of the total emissions. Following this, insulation materials contribute a smaller share, amounting to 9.59% of the total emissions.

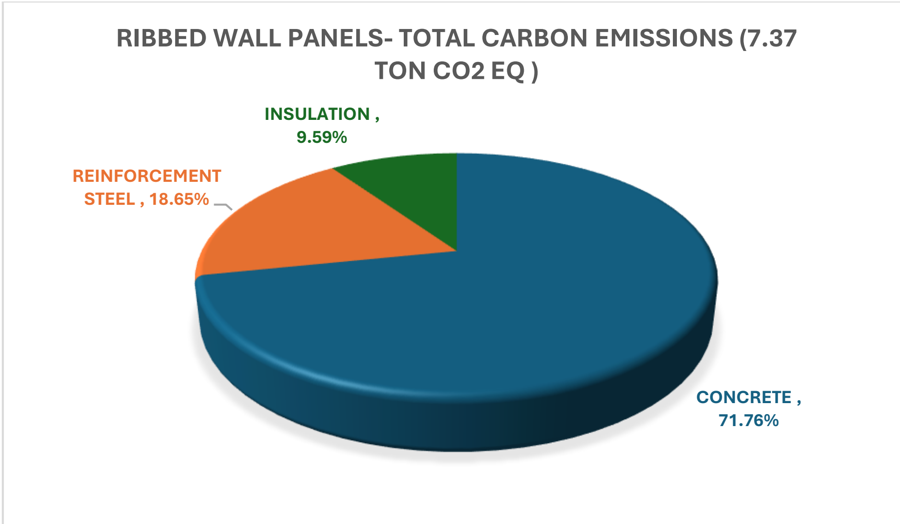


Figure 59: Ribbed wall panels' carbon emissions by material

When analyzing carbon emissions by construction stage, there are noticeable fluctuations among the different phases, as illustrated in Figure 60. Manufacturing building materials presents the largest emissions, accounting for nearly 40% of the total emissions with 6.3 tons of CO2 equivalent, followed by the transportation of these materials.

It is essential to highlight that concrete is the predominant contributor to embodied carbon in the manufacturing and transportation stages. Conversely, reinforcement steel emerges as a slightly higher contributor to emissions when considering material waste than concrete. However, the emissions generated by material waste are relatively minimal, comprising only 1% of the total emissions.

Additionally, the emissions from the extra transportation introduced by offsite practices (A4b) are the least significant, contributing just below the material waste emissions by 0.1 tons of CO_2e. This positions the additional transportation as a minor factor in the overall carbon footprint.

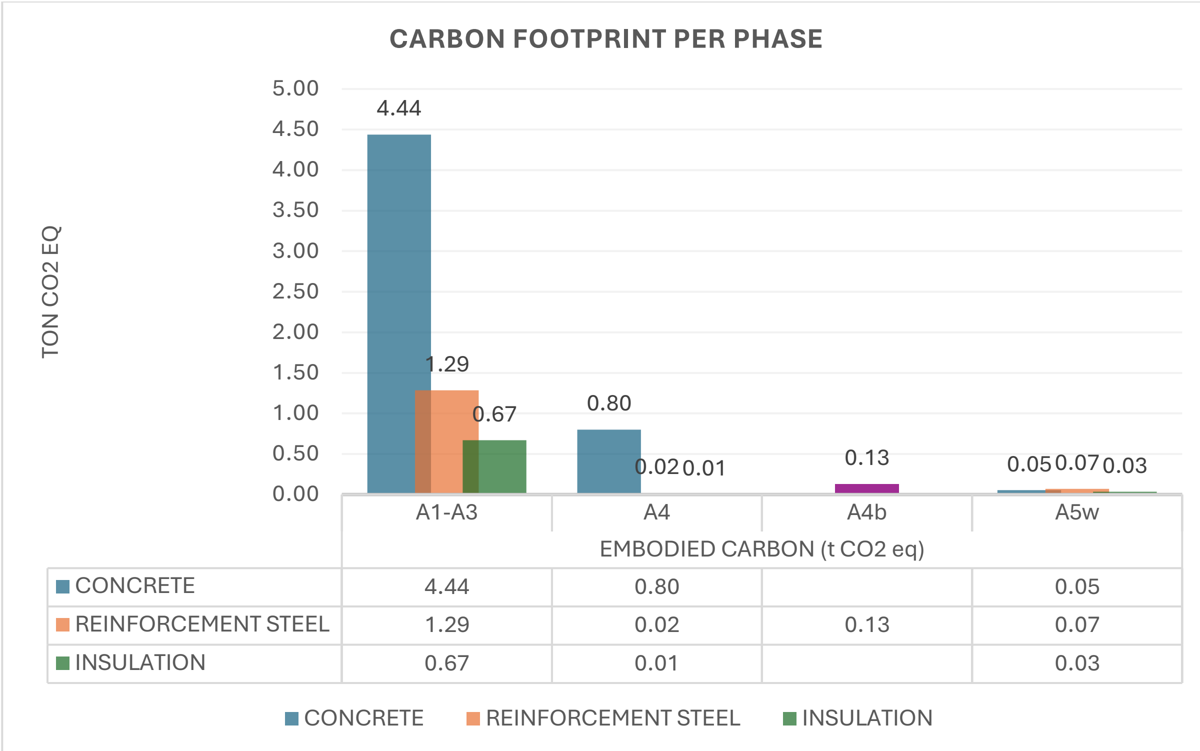


Figure 60: Ribbed wall panels carbon emissions by stage

5.1.3.2 Costs of Material

Figure 61 presents the total materials cost for ribbed walls and summarizes the cost percentages for each material based on Table 14. The total cost was recorded as $4,235.88. Most of the expenses were attributed to concrete, accounting for 82% of the total cost ($3,484.8). Following concrete, reinforcement steel was the next significant expense, contributing 16% of the total cost ($662.08), over 65% less than the cost of concrete. Conversely, insulation was the least expensive material, accounting for just 2% of the overall expenses. This represents 14% less than the cost of reinforcement steel and 80% less than the cost of concrete.

Table 14. Ribbed walls costs

Material	**Quantity**	**Units**	**Unit cost**	**Total cost**
Concrete 40MPa	10.89	m3	$320.00	$3,484.80
Mesh 6*6 10-10	115.60	m2	$ 0.37	$ 43.25
Rebar 10M	1473.77	ft	$ 0.42	$ 618.83
Insulation	224.60	ft3	$ 0.40	$ 89.01
			Grand Total	**$4,235.88**

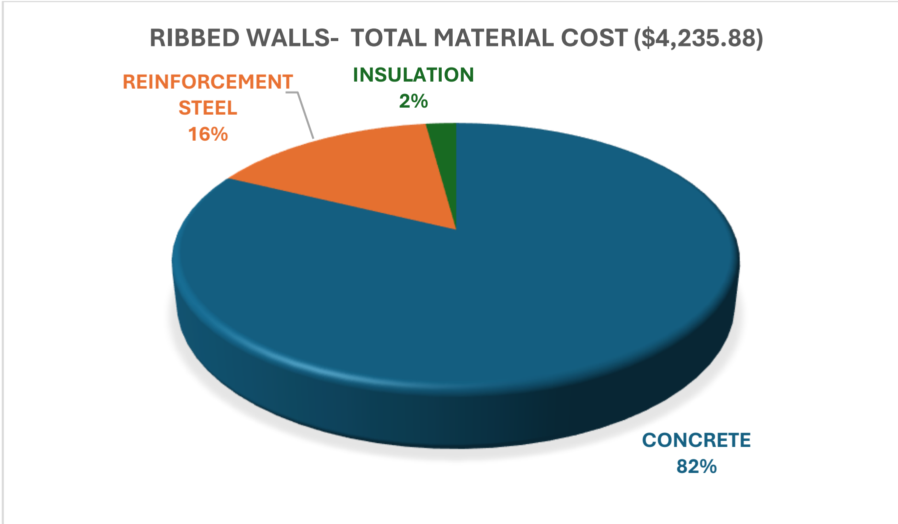


Figure 61: Overall Cost and Material Percentage Breakdown of Ribbed Walls

5.1.4 Overall comparison

5.1.4.1 Material Consumption

As illustrated in Figure 62, the ribbed wall panel method stands out for its superior efficiency in concrete and reinforcement steel consumption, outperforming the Insulating Concrete Form (ICF) and Concrete Sandwich walls. Specifically in concrete, it consumes 55% and 54% less material than its opponents. Regarding reinforcement steel, results showed a slightly less but significant contrast of over 30% and 40% compared to ICF and Concrete Sandwich wall methods respectively.

In contrast, the ICF and Concrete Sandwich wall approaches did not exhibit significant variations. The concrete differed by less than 1 ton of material, equivalent to a 1.55% difference, while the reinforcement steel in sandwich panels showed an increase of 17%. The higher reinforcement steel usage in concrete sandwich panels is attributed to the additional rebar required to connect the two concrete layers (shear connectors).

On the other hand, insulation results diverged, with Concrete Sandwich panels slightly edging out at 0.14 tons of CO_2e, closely followed by Ribbed panels with 0.16 tons of CO_2e, resulting in a modest difference of about 12%. In contrast, ICF walls exhibited an increase of over 60% in insulation usage.

This difference in insulation volume can be attributed to the different construction methods rather than the square footage of the walls, which remains consistent across the three methods. Ribbed walls consume slightly more insulation because the material is installed not only on the surface of the concrete shell but also along the sides of the ribs. This additional coverage increases the overall insulation usage. In contrast, ICF walls consumed more than double the insulation compared to the other methods due to the thickness of the insulation boards. ICF walls incorporate two insulation boards that are 2 ¾ inches thick on each side, totaling 5.5 inches in overall thickness. This significantly contributes to the higher volume and associated CO2 emissions, underscoring the impact of construction method choices on material consumption and environmental performance.

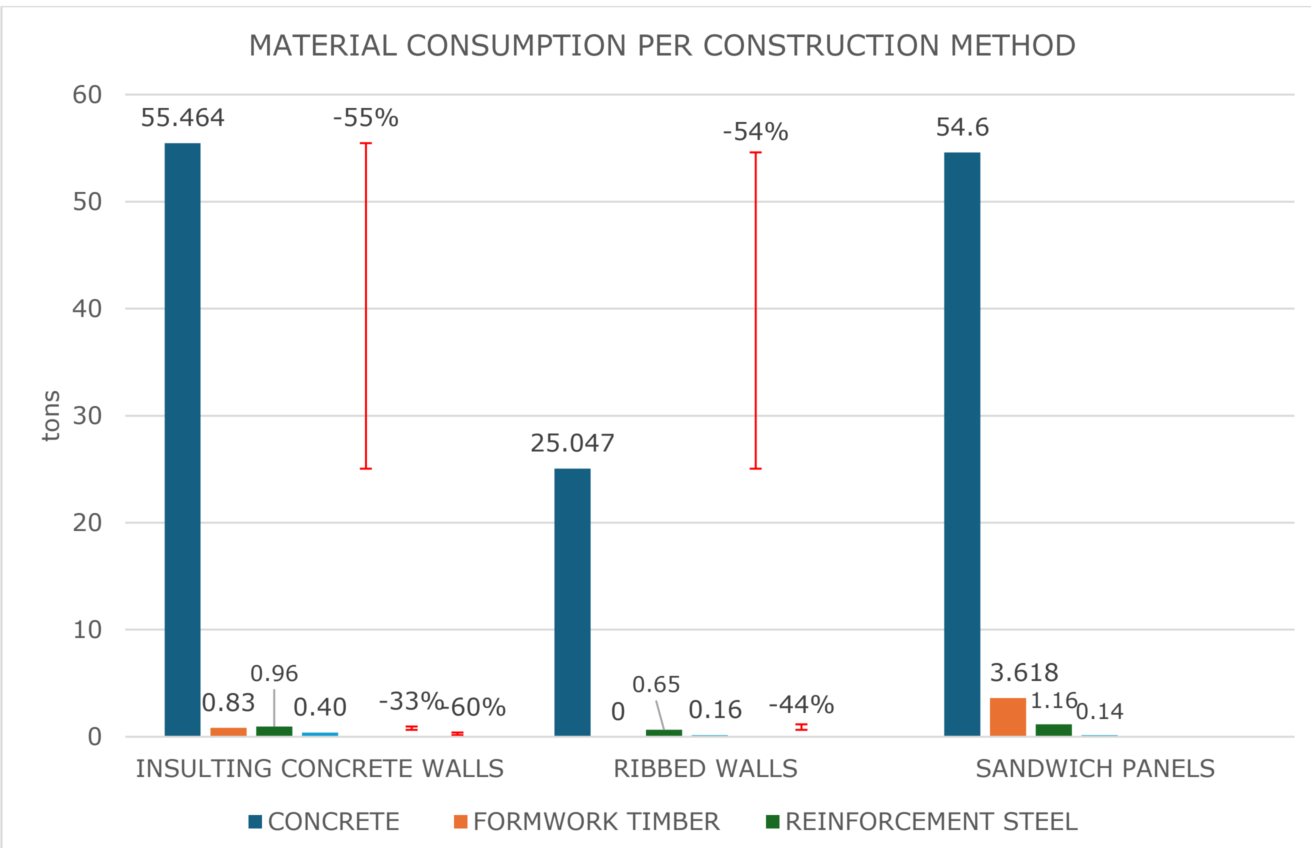


Figure 62: Basement walls material consumption comparison

5.1.4.2 Carbon Emissions

Figure 63 reveals the environmental impact of the different wall panel methods. Insulating Concrete Form walls contribute the most to carbon emissions in the overall study, with a total of 14.94 tons of CO_2e. In contrast with Concrete Sandwich walls, it shows a slight decrease of 5% in the material manufacturing stage and a significant mitigation of footprint in material waste of around 50%, but almost equal emissions related to transportation (A4).

Ribbed walls, on the other hand, demonstrate a significant reduction in almost all embodied carbon stages. The largest decrease is in material manufacturing, with almost 50%, followed by over 50% reduction in the transportation phase compared to competitors. The reduction of emissions from material waste is recorded as 81% in contrast with ICF walls and around 61% when compared with Concrete Sandwich walls.

Conversely, Concrete Sandwich panels and Ribbed walls present additional embodied carbon based on stage A4b in the study. Since both building methods are offsite, they introduce additional transportation of precast panels for their installation to the site, contributing to 0.30 and 0.14 tons of CO_2e emissions, respectively.

Transportation distances significantly impact the embodied carbon of construction methods. For instance, the study assumed a maximum transportation distance of 50 km for precast panels, as mentioned in Chapter 4.10, "Carbon Footprint Analysis and Embodied Carbon Factors." If this distance increases, so do the transportation emissions from off-site construction methods (A4b). Additionally, material manufacturers' transportation distance, considered up to 300 km in this study, can also affect the carbon emissions of each construction method.

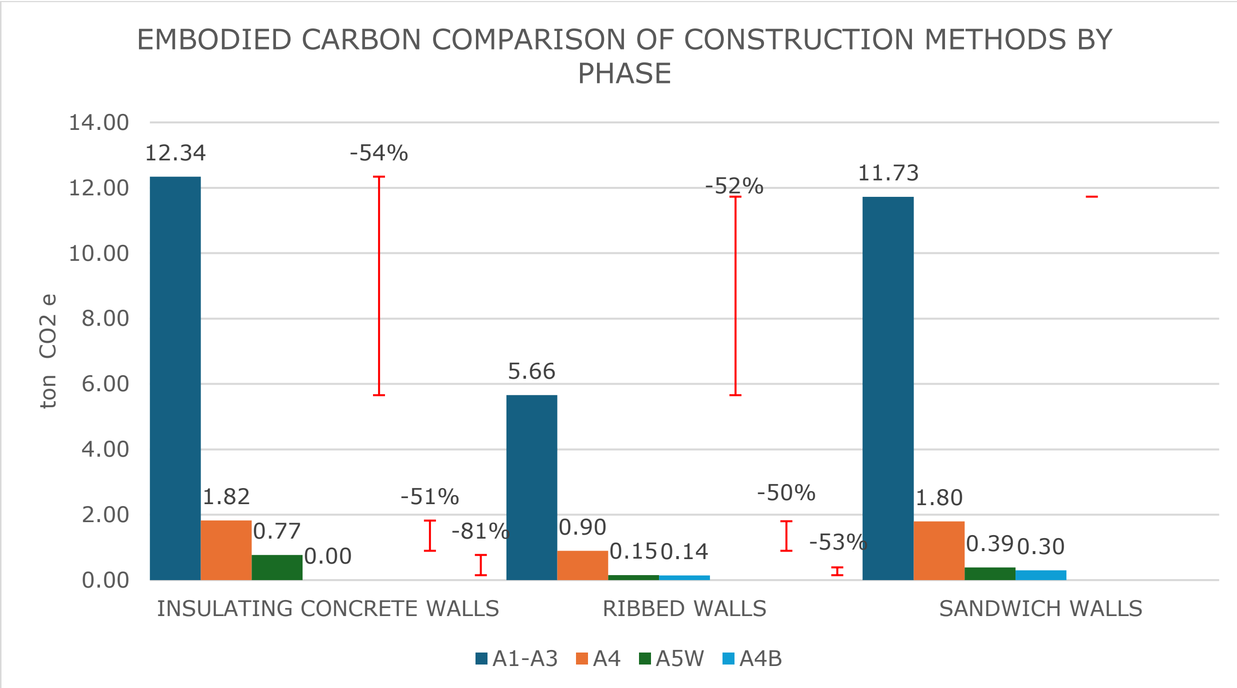


Figure 63: Basement walls embodied carbon comparison

5.1.4.3 Costs of Material

Figure 64 illustrates the overall cost of materials, showing that ICF walls recorded the highest total cost at $15,709.44. This was followed by concrete sandwich panels, which accounted for a total cost of $11,691.81, representing a difference of nearly 26%. The expenses varied among the materials: the cost of concrete used in ICF walls was only 1.5% higher than in sandwich panels. Conversely, sandwich panels had lower reinforcement costs by $522 (22.2%) and lower insulation costs by 96.8% ($6,864.53). On the other hand, the cost of timber formwork for ICF walls was $2,422.40 less than for sandwich panels.

These trends can be attributed to the partial elimination of formwork in ICF walls. Incorporating ICF blocks reduces the need for timber formwork, resulting in cost savings. However, the higher cost of the ICF blocks leads to increased expenses for insulation.

In contrast, ribbed walls recorded the lowest costs ($4,235.88), around 64% and 73% lower than concrete sandwich panels and ICF walls. Regarding materials, the concrete costs for ribbed walls are over 40% less than their competitors. Additionally, when comparing reinforcement steel, ribbed walls represented the lowest cost, 72% less than concrete sandwich walls and 64% less than ICF walls. Moreover, insulation and timber formwork costs recorded the highest decreases compared to ribbed walls, with insulation expenses being 99% cheaper than ICF and 61% cheaper than sandwich panels.

Finally, expenses for formwork were eliminated in ribbed walls, as this construction method does not require a formwork structure, resulting in 100% savings on formwork-related costs.

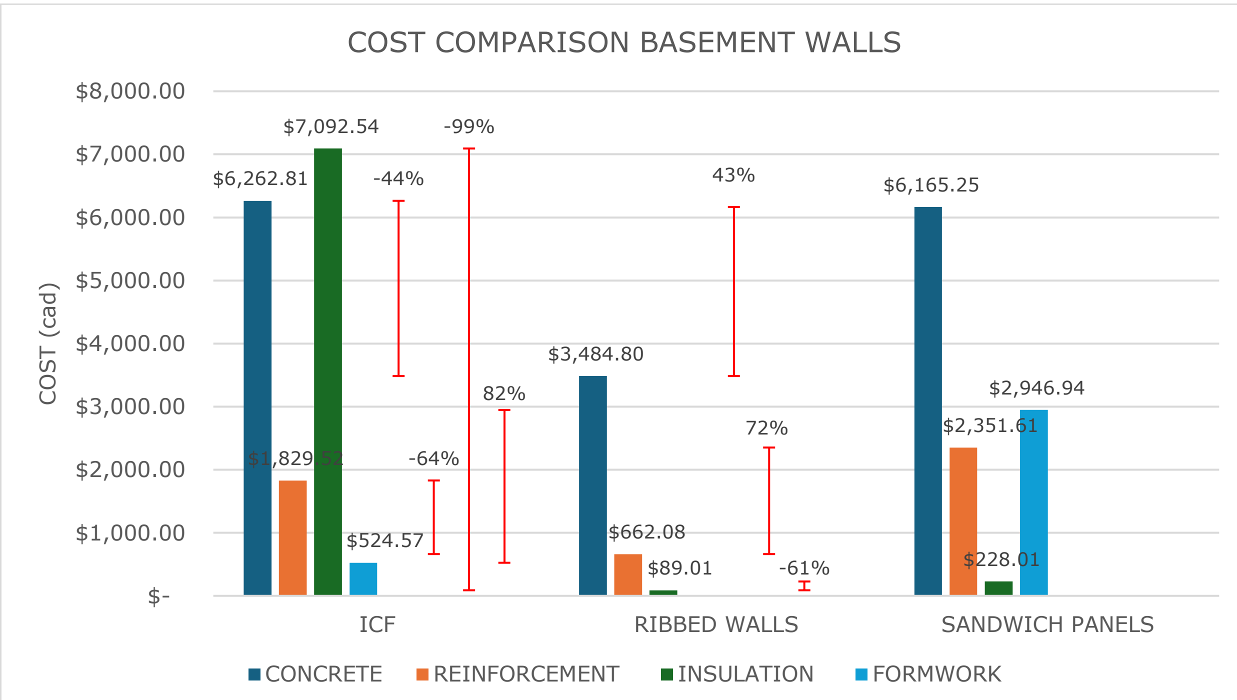


Figure 64: Basement walls material cost comparison

5.2 Concrete Slabs

5.2.1 Cast-In-Place Slabs

The computations of carbon emissions and material costs is derived from Chapters 4.9, "Cost of Materials," and 4.10, "Carbon Footprint Analysis and Embodied Carbon Factors." Table 15 displays the material quantities for Cast-in-place slabs, which were obtained from the 3D REVIT model.

Table 15. Cast-in-place slabs material consumption

Material	Quantity (kg)
Concrete	90,338.26

Reinforcement steel	2,503.05
Formwork timber	9,252

5.2.1.1 Carbon emissions

Cast-in-place slab construction shows significant total carbon emissions of 24.39 tons of CO_2e. As shown in Figure 65, the majority of these emissions stem from concrete, which alone is responsible for 73.71% of the total emissions, equivalent to 17.98 tons of CO_2e. This places concrete far ahead of the next major contributor, reinforcement steel, which accounts for 21.85% or 5.33 tons of CO_2e.

While essential in construction, formwork timber contributes a smaller yet notable portion to the overall emissions. It represents 4.44% of the total, equating to 1.08 tons of CO_2e. This demonstrates that concrete remains the predominant source of carbon emissions in the cast-in-place slab method, significantly outpacing reinforcement steel and formwork timber in its environmental impact.

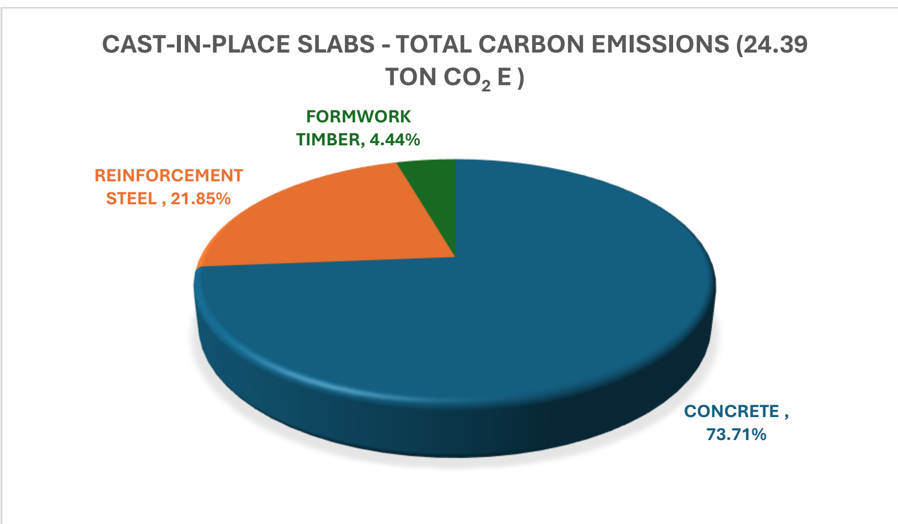


Figure 65: Cast-in-place slabs carbon emissions by material

The carbon footprint of cast-in-place slabs by construction stages is illustrated in Figure 66, where a breakdown of materials is provided.

As expected, concrete highlighted in blue is responsible for the highest emissions in manufacturing materials, transportation, and material waste. On the other hand, the reinforcement steel trend varies among the different stages. It leads after concrete in the manufacturing phases, but it experiences a drop in transportation and waste of material, where it is slightly overpassed by formwork timber. This tendency is derived from the large material volumes of timber used for the forming structure.

In construction phases alone, transportation of materials is the second largest source of emissions after manufacturing, accounting for almost 13% of the total emissions and below manufacturing by around 68% (16.7 tons of CO_2e).

On the contrary, material waste recorded the least environmental impact, representing just 6% of emissions.

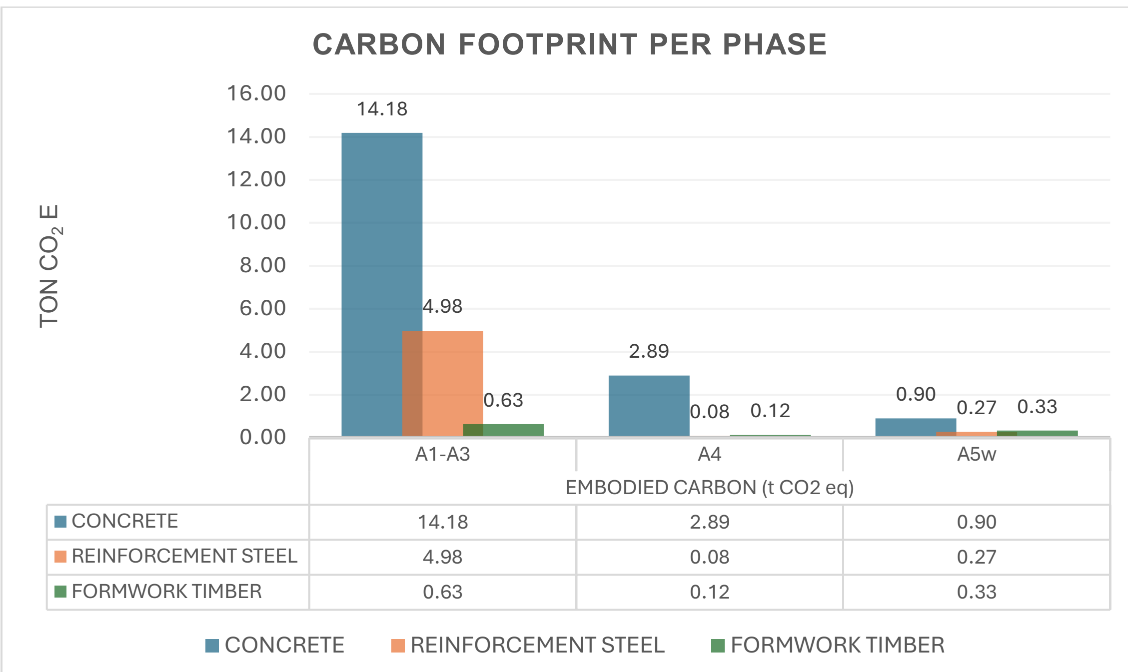


Figure 66: Cast-in-place slabs carbon emissions by stage

5.2.1.2 Costs of Material

As depicted in Figure 67 and Table 16, the total material cost for the slabs amounted to $21,794.66. Formwork costing $8,871.71 exceeded the expenses for reinforcement steel by more than 28%, with reinforcement steel costing $2,725.01. This is due to the large amounts of timber used for formwork, as traditional practices do not minimize its use, thereby introducing inefficiencies and additional costs. Reinforcement steel is the least expensive of all materials, with 12.5%, while concrete represents the highest expenditure at 46.8% ($10,197.73).

The substantial volume of concrete required for these slabs is evident in the overall cost distribution, highlighting a significant difference between the costs of reinforcement steel and formwork timber, which account for 34% and 6% of the total cost, respectively. This considerable difference underscores the financial impact of the extensive use of concrete in constructing the cast-in-place slabs.

Table 16. Cast-in-place slabs costs

Material	Quantity	Units	Unit cost	Total cost
Concrete 35MPa	37.63	m3	$ 271.00	$10,197.73
Rebar 10M	1083.92	ft	$ 0.42	$ 455.13
Rebar 15M	1633.04	ft	$ 0.99	$1,610.24
Rebar 25M	278.5	ft	$ 2.37	$ 659.64
Formwork timber	14.86	m3	$ 380.12	$5,648.63
Formwork plywood	86	sheet	$ 37.48	$3,223.28
			Grand Total	**$21,794.66**

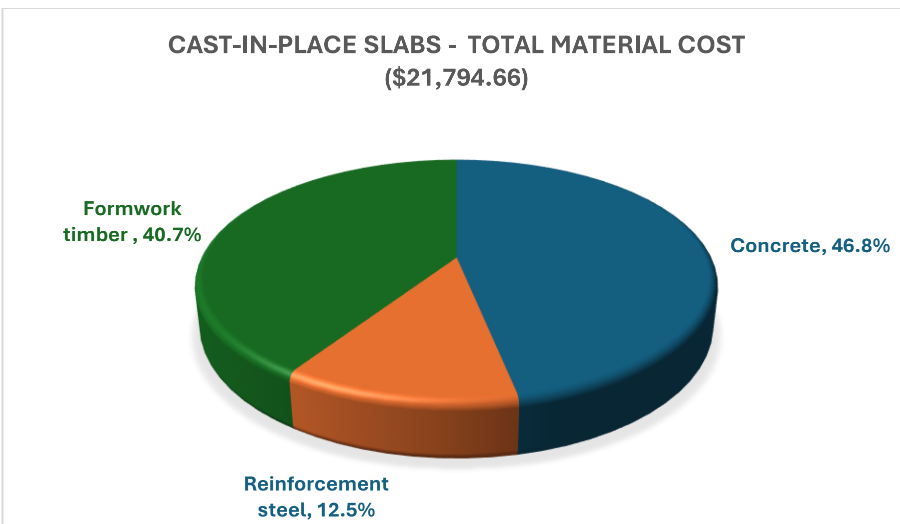


Figure 67: Overall Cost and Material Percentage Breakdown of Cast-in-place slabs

5.2.2 Hollow-core Slabs

Carbon emissions and material costs were evaluated using the calculations in Chapters 4.9 "Cost of Materials" and 4.10 "Carbon Footprint Analysis and Embodied Carbon Factors". Table

17 shows the quantities of materials for hollow-core slabs, as derived from the 3D REVIT model.

Table 17. Hollow-core slabs material consumption

Material	**Quantity (kg)**
Precast concrete	70,882.97
In situ concrete	29,057.87
PC strands reinforcement	979.43
Reinforcement steel	590.28
Formwork timber	3,210.00

5.2.2.1 Carbon emissions

As discussed in section 3.2.2 “Hollow-core slabs,” they require minimal formwork for the top layer on the hollow-core planks. Consequently, emissions related to this contribute only 1.63% of the total embodied carbon, equating to 0.38 tons out of 22.05 tons of CO_2e, as depicted in Figure 68. While contributing a notable 14.5% (3.34 tons of CO_2e), reinforcement steel still falls significantly below concrete emissions by almost 70%.

Concrete, as usual, is the largest carbon emitter, accounting for most of the total embodied carbon. In contrast, formwork timber emissions are minimal, being a tiny fraction compared to the substantial impact of concrete and reinforcement steel.

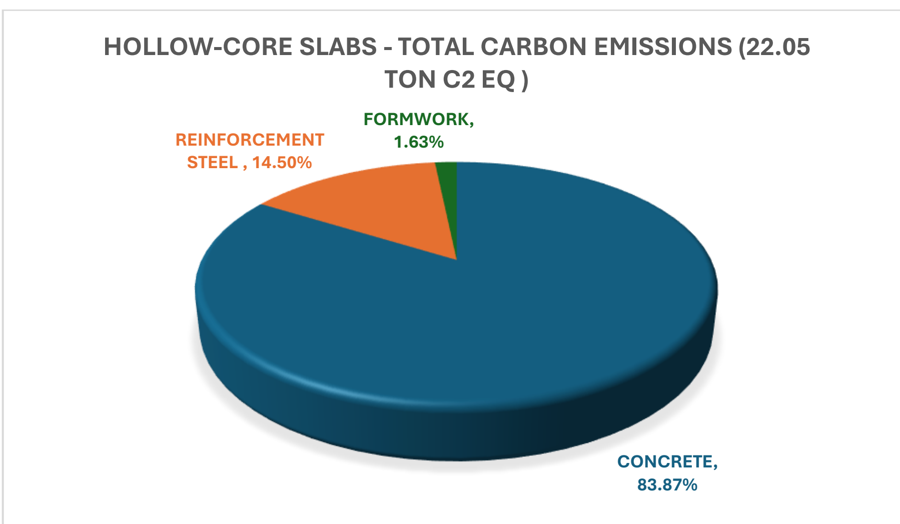
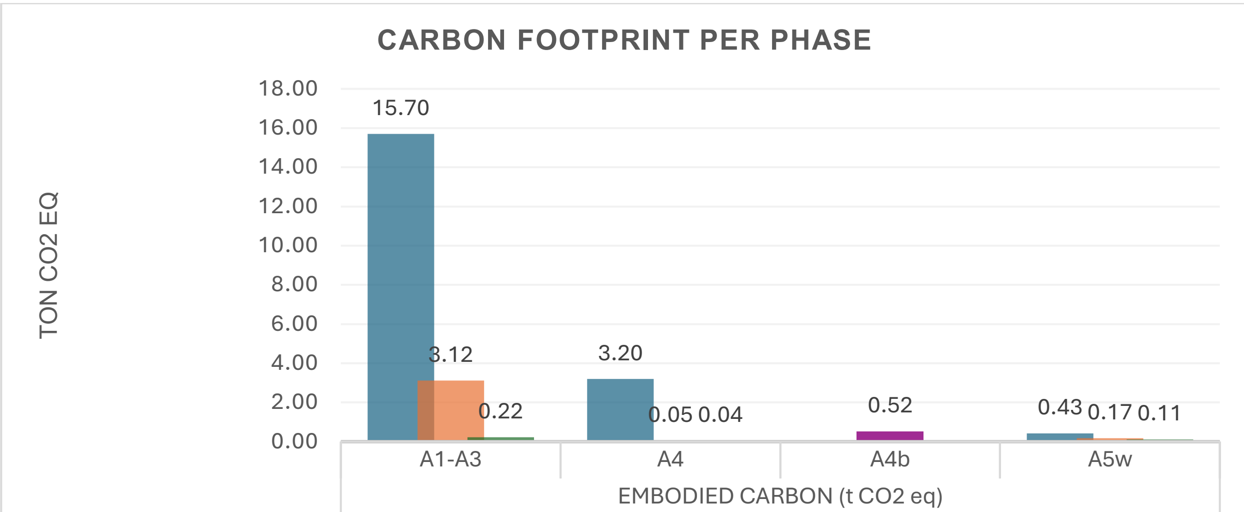


Figure 68: Hollow core slabs carbon emissions by material

The results illustrated in Figure 69 reveal a consistent trend where concrete is the largest contributor to carbon emissions, followed by reinforcement steel and timber across all building phases. The manufacturing stage is the most impactful, accounting for over 80% (19.04Co2e) of the total embodied carbon. On the other hand, transportation from the manufacturer to the construction site represents around 15% (3.29Co_2e), nearly 65% less than the manufacturing emissions.

In contrast, transportation from the offsite facility to the installation site has the least environmental impact, contributing only 2.35% of the total emissions. This is slightly lower than material waste, which recorded 0.69 tons of CO_2e emissions.



	A1-A3	A4	A4b	A5w
CONCRETE	15.70	3.20		0.43
REINFORCEMENT STEEL	3.12	0.05	0.52	0.17
TIMBER FORMWORK	0.22	0.04		0.11

Figure 69: Hollow-core slabs carbon emissions by stage

5.2.2.2 Costs of Material

The pie chart below and Table 18, illustrate the total material cost of hollow-core slabs, amounting to $22,456.62. Concrete is the most expensive material, costing $11,659.20 and representing 51% of the overall expenses. This significant portion underscores the critical role of concrete in the structural integrity of hollow-core slabs.

Reinforcement steel is the second most expensive material, costing $7,678.6. It accounts for approximately 35% of the total expenses.

Formwork timber, on the other hand, contributes the least to the overall cost, making up roughly 14% ($3,118.83). Although it is necessary for shaping and supporting the concrete during curing, its lower cost relative to concrete and steel highlights its less intensive use and lower material expense.

Table 18. Hollow-core slabs costs

Material	Quantity	Units	Unit cost	Total cost
Concrete 35MPa	41.64	m3	$ 280.00	$11,659.20
Strands 9.5 mm	21177.22	ft	$ 0.30	$6,444.07
Mesh 6*6 6-6	2171.06	m2	$ 0.57	$1,234.52
Formwork timber	1.5	m3	$ 380.12	$ 570.18
Formwork plywood	68	sheet	$ 37.48	$2,548.64
			Grand Total	**$22,456.62**

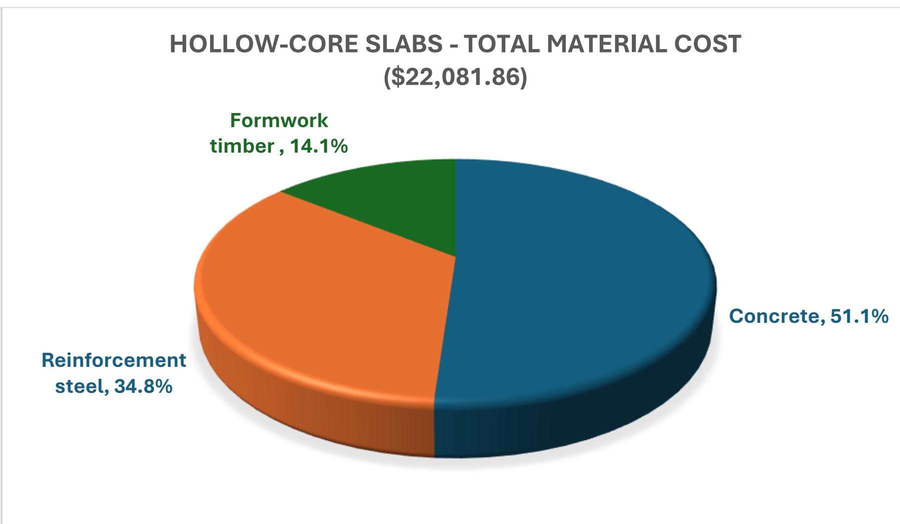


Figure 70: Overall Cost and Material Percentage Breakdown of hollow-core slabs

5.2.3 Ribbed Slabs

The assessment of carbon emissions and material costs is based on calculations from Chapters 4.9, "Cost of Materials," and 4.10, "Carbon Footprint Analysis and Embodied Carbon Factors." Table 19 outlines the material quantities for ribbed slabs, sourced from the 3D REVIT model.

Table 19. Ribbed slabs material consumption

Material	Quantity (kg)
Concrete	57,569
Reinforcement steel	2,474.25

5.2.3.1 Carbon emissions

Figure 71 showcases ribbed slabs' total embodied carbon emissions, amounting to 17.43 tons of CO_2e. Reinforcement steel contributes 30.22% (5.27 tons of CO_2e) to the total emissions, while concrete is the primary emitter, accounting for 69.78% (12.16 tons of CO_2e). This highlights the predominant role of concrete in the carbon footprint of ribbed slab construction, with reinforcement steel also playing a significant, though smaller, role.

This detailed breakdown clearly shows the significant contributions of each material to the overall carbon footprint of ribbed slab construction.

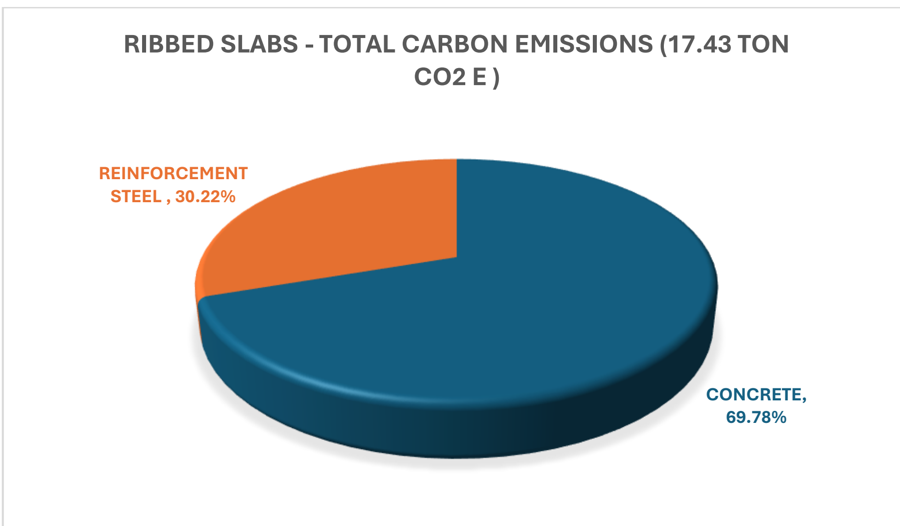


Figure 71: Ribbed slabs carbon emissions by material

The carbon emissions of ribbed slabs, divided by stages and each material's contribution, are illustrated in Figure 72. Concrete dominates in almost all stages, particularly in manufacturing materials, accounting for over 50% of overall emissions. Concerning the transportation of materials, concrete's contribution exceeds 95%. In contrast, emissions from material waste show a different pattern, with reinforcement steel contributing almost 70% of the emissions, breaking the overall trend.

Additionally, emissions from transportation between the precast facility and the installation site are slightly lower than from material waste by approximately 23%.

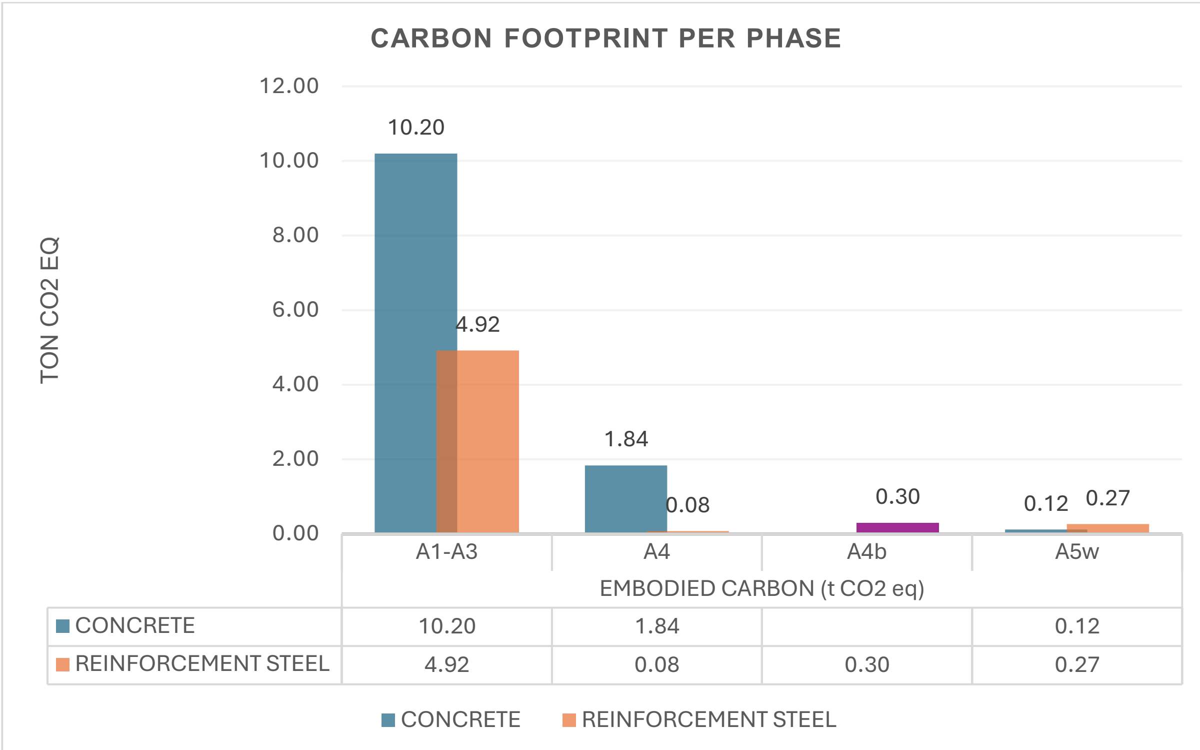


Figure 72: Ribbed slabs carbon emissions by stage

5.2.3.2 Costs of Material

Figure 73 and Table 20 present the total material cost for the ribbed slab construction method and a percentage breakdown by material. Concrete represents the highest cost, with 77.80%, equivalent to $8009.60.

On the contrary, reinforcement steel is the second most expensive material, contributing 22.2% ($2,285.94). This allocation highlights the significant expense associated with concrete in this construction method, while rebar, although crucial, represents a smaller portion of the total cost.

Table 20. Ribbed slabs costs

Material	Quantity	Units	Unit cost	Total cost
Concrete 40MPa	25.03	m3	$ 320.00	$ 8,009.60

Mesh 6*6 6-6	195.20	m2	$ 0.57	$ 111.00
Rebar 15M	1525.42	ft	$ 0.99	$1,504.12
Rebar10M	1082.42	ft	$ 0.42	$ 454.50
Rebar 20M	91.33	ft	$ 2.37	$ 216.32
			Grand Total	**$10,295.54**

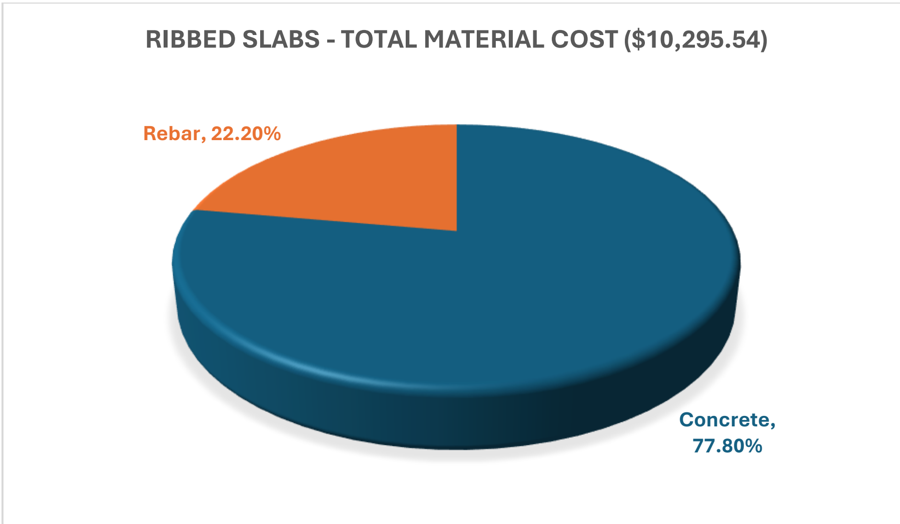


Figure 73: Overall Cost and Material Percentage Breakdown of ribbed slabs

5.2.4 Overall comparison

5.2.4.1 Material Consumption

Figure 74 illustrates the material consumption comparison across all slab building practices. Concrete is the most used material in all construction methods, particularly in hollow-core slabs, which record the highest volume of concrete at almost 100 tons. Cast-in-place slabs follow, consuming nearly 10% less concrete. In contrast, ribbed slabs use the least concrete, with 57.6 tons, 42%, and 36% less than hollow-core and cast-in-place slabs.

However, ribbed slabs do not show a reduction in the use of reinforcement steel; they consume more than hollow-core slabs. While ribbed slabs use 1% less steel than cast-in-place slabs, they consume almost a ton (37%) more than hollow-core slabs.

Regarding formwork timber, cast-in-place slabs recorded the highest usage compared to hollow-core slabs, consuming 65% more material. This difference is due to the reduced formwork requirements of hollow-core slabs.

The extensive use of timber formwork in cast-in-place slabs results in high material consumption, surpassing hollow-core and ribbed slabs by a significant difference. This highlights the inefficiency of traditional construction practices in providing solutions in this manner. In contrast, most off-site construction methods significantly reduce or eliminate the need for formwork by casting elements at ground level, thereby avoiding the need for additional material to brace and support loads against gravity.

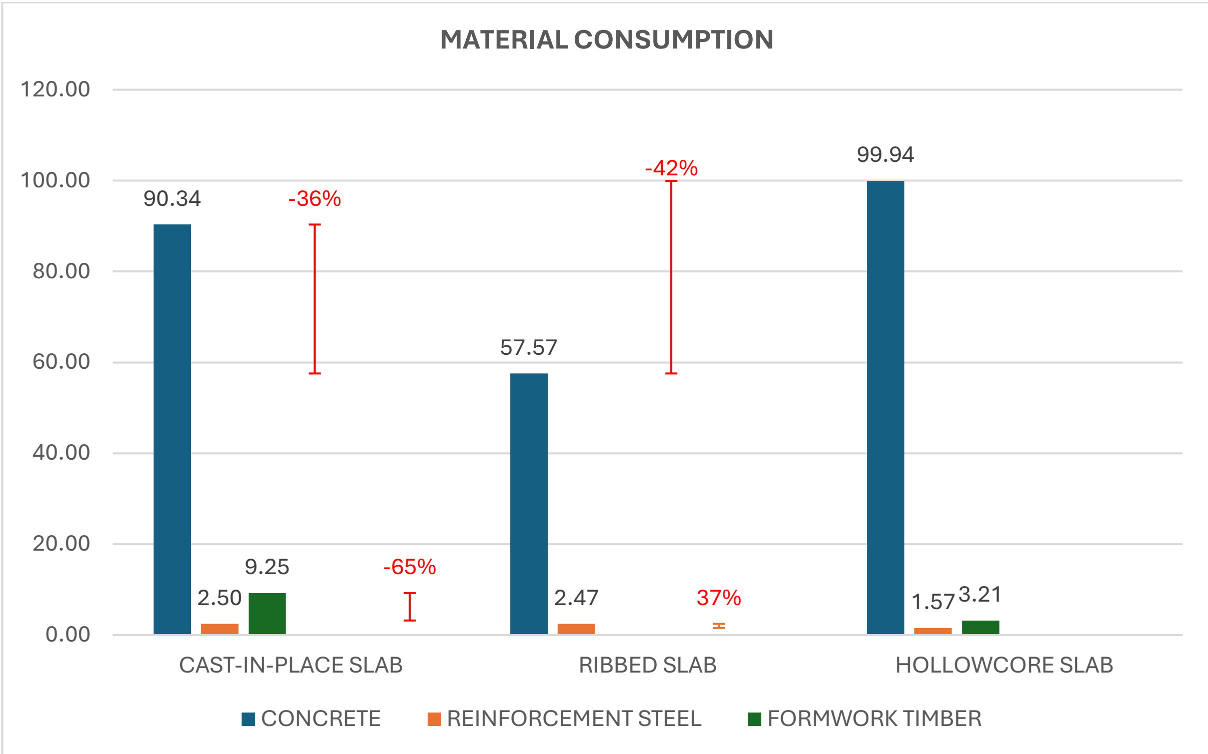


Figure 74: Concrete slabs material consumption comparison

5.2.4.2 Carbon Emissions

As illustrated in Figure 75, comparing embodied carbon emissions for different slab construction methods reveals significant variations at each process stage.

The highest emissions were recorded in the manufacturing stages (A1-A3), marking these stages as the largest environmental impact contributors. Flat slabs exhibited the highest emissions, leading by approximately 4% and 27% compared to hollow core slabs and ribbed slabs, respectively. This phase accounts for around 80% of the total embodied carbon for each construction method.

Transportation of materials is the second-most polluting contributor. Hollow-core slabs recorded the highest emissions in this category, with a maximum of 3.29 tons of CO_2e, followed by cast-in-place and ribbed slabs. Ribbed slabs reduced by over 30% in transportation emissions compared to the other methods.

Regarding material waste, cast-in-place slabs exhibited the highest emissions, exceeding 70% compared to ribbed slabs. In contrast, Hollow-core slabs reduced waste emissions by 54% compared to cast-in-place slabs. This demonstrates that off-site construction methods can significantly decrease embodied carbon associated with material waste, primarily due to the lower percentages of material waste in operations conducted in controlled environments.

Lastly, transportation from the offsite facility to the installation site had an environmental impact close to material waste but slightly lower. This accounted for 1.7% of total emissions for ribbed slabs and 2.2% for hollow-core slabs.

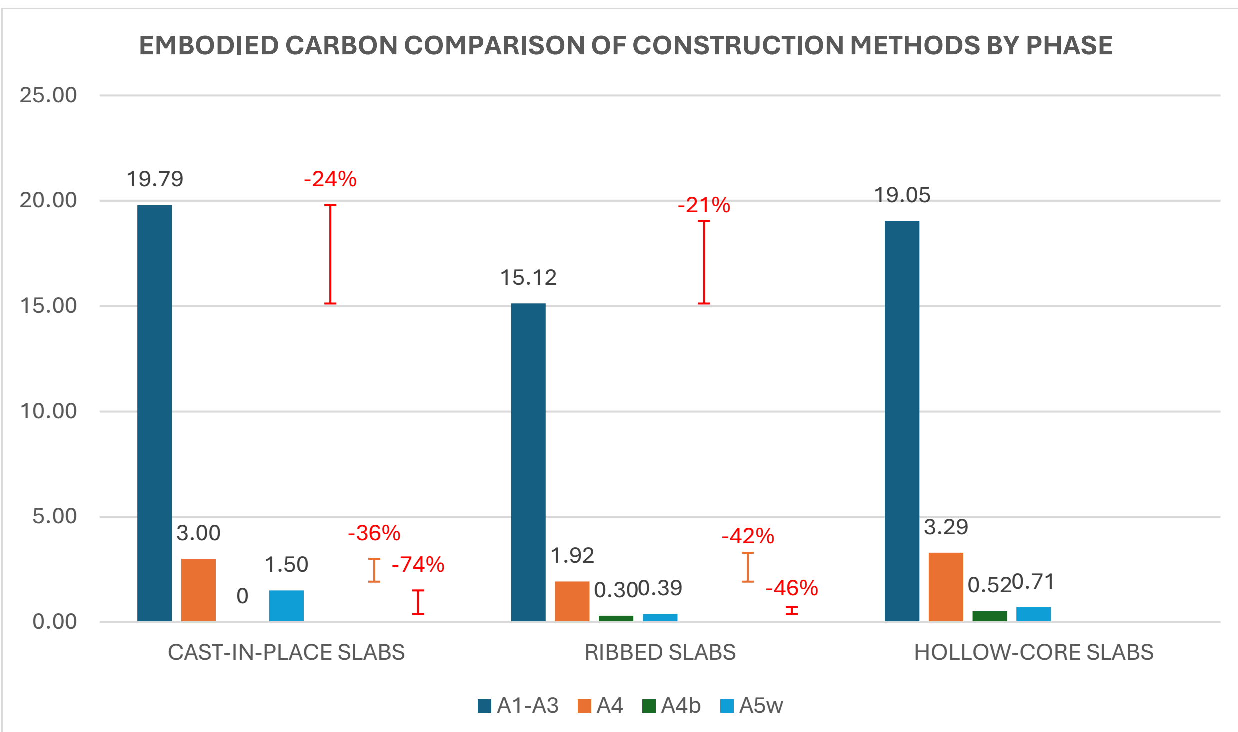


Figure 75: Concrete slabs embodied carbon comparison

5.2.4.3 Costs of Material

Figure 76 illustrates a cost comparison of concrete slabs divided by construction method, providing a cost breakdown by building materials. With a total cost of $31,992.40, cast-in-place slabs emerged as the most expensive construction method. In contrast, hollow-core slabs were 30% less expensive, amounting to $22,456.62, representing a difference of $9,535.76 in overall costs.

When comparing the material costs, cast-in-place slabs had higher formwork expenses than hollow-core slabs but lower concrete and reinforcement steel costs. Specifically, concrete costs for cast-in-place slabs were 9.6% less but almost 65% more expensive in terms of formwork. However, the reinforcement steel costs for hollow-core slabs almost tripled those of cast-in-place slabs, showing a difference of $4,953.58, or 65%.

Ribbed slabs, on the other hand, were the most economical construction method, costing 53% less than cast-in-place slabs and 54% less than hollow-core slabs. Regarding material costs, ribbed slabs show a decrease overall. For concrete, ribbed slabs were 21% cheaper than cast-in-place slabs and 29% less expensive than hollow-core slabs.

Regarding reinforcement steel, ribbed slabs incurred the least cost, 16% cheaper than cast-in-place slabs and 70% less expensive than hollow-core slabs. As for formwork timber, hollow-core slabs recorded costs 65% lower than cast-in-place slabs.

Ribbed slabs saved 100% on formwork timber costs, as this construction method does not require additional formwork structures for molding.

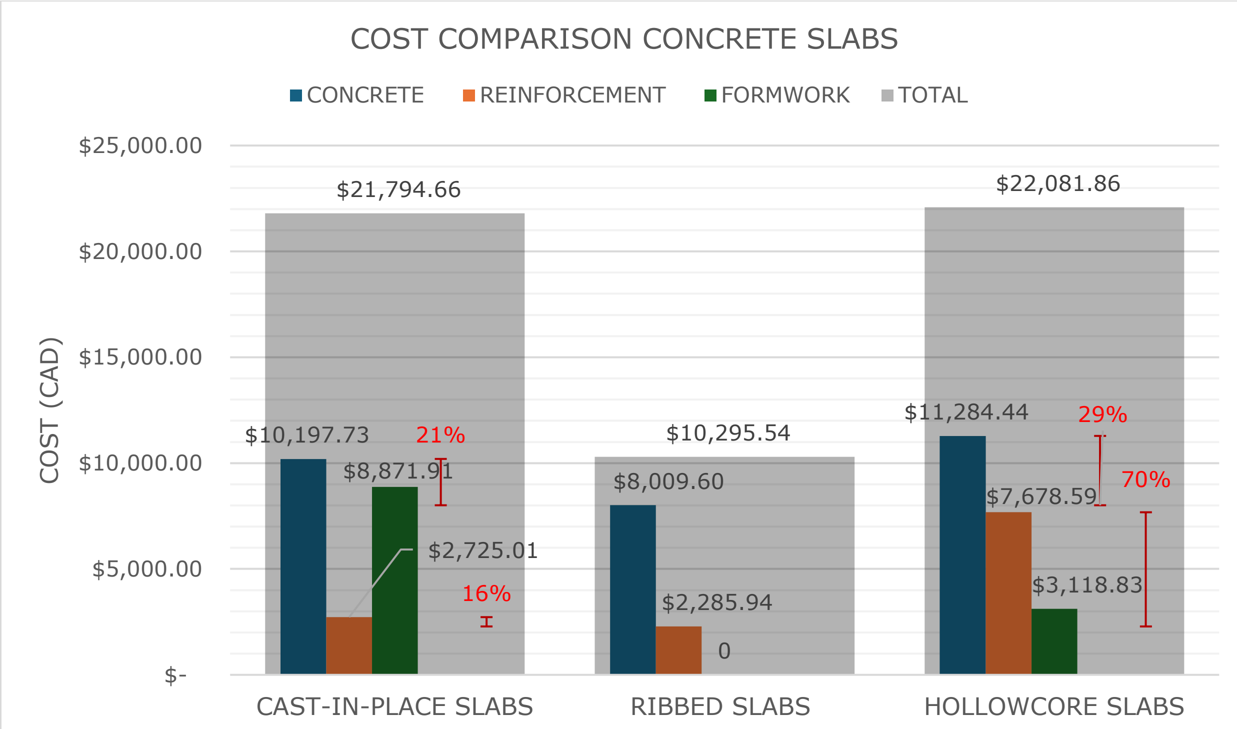


Figure 76: Concrete slab total cost comparison

5.3 Limitations encountered during structural design and architectural modeling.

Modifications to the design of openings in ICF walls, as shown in Figure 77, were necessary due to limitations outlined in the code and design prescriptive. All openings have been adjusted, lowering them from 6 to 11 inches from the top of the basement wall. Additionally, two windows were reduced in width by 50%, and one of the interior walls was removed as it did not comply with the code minimum distance requirements from the corner of the wall to the opening, rendering it too short to accommodate a door.

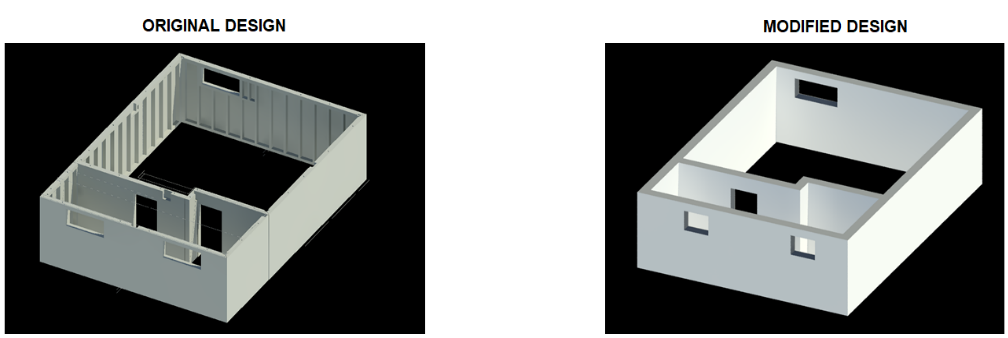


Figure 77: Design modifications in ICF walls

CHAPTER 6: CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1 Research Summary

This analysis compares various construction methods' cost implications and embodied carbon under consistent project conditions, constraints, location, and transportation distances. The results show an overall reduction in carbon emissions and cost savings with ribbed structures. However, these findings may vary if building practices are compared under different scenarios, such as construction location, transportation distances, material types, site temperature conditions, choice of manufacturers, and seismic activity.

The manufacturing stage represents the largest CO2 emissions overall, followed by material transportation. Efforts to reduce material consumption in the construction industry are critical since these influence carbon emissions at all stages.

Concrete records large emissions and costs in all construction methods. To reduce costs and environmental impacts, the reduction of cementitious materials, replacement, or alterations should be urgently investigated.

Insulating Concrete Form (ICF) walls significantly enhance building insulation, providing double the insulation compared to Sandwich panels and ribbed walls. Additionally, ICF walls reduce expenses and carbon emissions by partially eliminating the need for formwork with ICF blocks that serve as molds. However, this solution introduces another challenge: the high costs and environmental impact of the insulation itself.

Even though formwork timber represented low carbon emissions in all construction methods, it accounted for significant costs in some building practices, specifically in hollow-core slabs at 14% of overall expenses, concrete sandwich panels at 17%, and 27.7% for cast-in-place slabs.

Embodied carbon factors may vary by construction method due to the manufacturing process, type of materials used, mode of transportation, and operations. It is crucial to carefully evaluate and compare the environmental implications of different construction processes, considering their material consumption and the associated carbon emissions.

Although phase A4b increases embodied carbon in offsite construction, its overall impact is small compared to other stages. However, the distance between the precast factory and the installation site is essential. Longer transportation distances mean higher $CO2$ emissions, which can be a disadvantage for offsite construction methods if the factory is far from the site as opposed to onsite building practices.

Similarly, the distance from the material manufacturer to the installation site should be carefully considered. This can significantly impact carbon emissions and influence the choice of construction method.

Material waste and its embodied carbon (A5w) are significantly reduced in controlled environments. Therefore, off-site construction methods present a promising solution to address these issues.

Limitations of Insulating Concrete Form Walls affect the system's freedom of design and, consequently, natural lighting. Making openings smaller in width and lowering them from the top of the wall does not allow room for big windows in a basement wall, introducing a problem to the final product.

Difficulties in constructing ICF walls are identified due to design limitations. The design is restricted to one floor below grade and a maximum of two stories above grade. Key limitations include a maximum building area of 3200 ft^2, a maximum foundation wall height of 12 ft, a main floor wall height of 16 ft, and a second-floor wall height of 10 ft. These constraints limit the use of this construction method to small residential buildings.

The embodied carbon results in this study indicate no significant differences between offsite and onsite construction methods. Instead, it emphasizes that the key factor influencing carbon emissions is the quantity of materials used. Overdesign and material choices have a substantial impact on emissions. Therefore, efforts to minimize material consumption and optimize structural design should be prioritized.

In conclusion, Ribbed panels are a promising option for resource-efficient and environmentally friendly concrete construction practices. They provide a solution for mitigating the current construction industry's carbon footprint, aligning with Canadian environmental initiatives and goals.

In summary, adopting Ribbed walls addresses environmental concerns through carbon footprint mitigation and offers a solution encompassing design flexibility, customization options, and superior space utilization. These attributes align closely with Canadian environmental initiatives and goals while fostering environments prioritizing sustainability and occupant satisfaction.

6.2 Research Contributions

- **Comprehensive Assessment of Structural Design Restrictions**: Identified potential restrictions and limitations in structural design across various construction methods, highlighting design freedom and natural lighting issues in Insulating Concrete Form (ICF) walls.
- **Fair Comparison of Construction Practices**: Provided a fair comparison of different construction practices by designing structures based on specific case study criteria, data, and constraints.
- **Detailed Material Volume Extraction using BIM**: Utilized Building Information Modeling (BIM) software, specifically Autodesk Revit, to model precise details and extract exact material volumes, enhancing the accuracy of embodied carbon calculations.
- **Carbon Emissions Analysis**: Assessed carbon emissions for various building practices, identifying the manufacturing stage as the largest contributor and highlighting the significant impact of concrete in all construction methods.
- **Life Cycle Assessment (LCA) Insights**: Identified the Life Cycle Assessment stages and materials with the most embodied carbon, emphasizing the need to investigate the reduction, replacement, or alteration of cementitious materials.
- **Cost-Effectiveness Evaluation**: Evaluated the cost-effectiveness of different construction practices, providing detailed insights into the cost contributions of each construction material and.
- **Formwork Structures Impact**: Highlighted the carbon emissions and costs introduced by formwork structures, noting their significant cost impact in certain methods like concrete sandwich panels, cast-in-place slabs and hollow core slabs.
- **Comparison of Offsite and Onsite Construction Methods**: Indicated no significant differences in embodied carbon between offsite and onsite construction methods, stressing that material quantity and overdesign are key factors influencing emissions.

- **Practical Implications for Construction Practices**: Provided practical insights for selecting cost-effective and environmentally friendly construction methods for basement walls and concrete slabs, aiding in the decision-making process for sustainable building practices.

6.3 Research limitations

- Limited data to perform a whole Life Cycle Analysis for all construction methods.
- Limited resources to assess the performance of designed structures in a finite element analysis software.
- Limited data and time to perform sensitivity analyses of costs.

6.4 Recommendations for future work

- **Assess and compare the whole Life Cycle Analysis (LCA) emissions:** Conduct a comprehensive evaluation of the environmental impact throughout each construction method's lifecycle to provide a more holistic understanding.
- **Add costs of labor, equipment, transportation, and indirect costs:** Include these factors in the analysis to provide an overall project cost estimation.
- **Explore different alternative materials:** Investigate various materials that could be used to decrease expenses and environmental impacts, potentially enhancing the sustainability of the construction methods.
- **Implement an analysis of each construction's mechanical, electrical, and plumbing (MEP) implications:** Assess how each construction method impacts the design, costs, time, material waste, and installation of MEP systems to identify potential challenges or efficiencies.
- **Examine construction times and operations:** Analyze each construction practice's duration and operational aspects to identify areas for potential improvement in efficiency and effectiveness.
- **Analyze the structural integrity of building practices:** Assess a comparison by analyzing construction methods' performance using a finite element analysis software.

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