

Review

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[Chia Paknahad](#)^{*}, [Mosleh Tohidj](#), [Ali Bahadori-Jahromi](#)

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Review

Improving the Sustainability of Reinforced Concrete Structures Through the Adoption of Eco-Friendly Flooring Systems

Chia Paknahad ^{1,*}, Mosleh Tohidi ² and Ali Bahadori-Jahromi ³

¹ Department of Civil Engineering and Built Environment, School of Computing and Engineering, University of West London, London W5 5RF, UK

² Department of Civil Engineering and Built Environment, School of Computing and Engineering, University of West London, London W5 5RF, UK

³ Department of Civil Engineering and Built Environment, School of Computing and Engineering, University of West London, London W5 5RF, UK

* Correspondence: chia.paknahad@uwl.ac.uk

Abstract: Following World War II, the swift economic growth in construction and the soaring demand in urban regions led to the excessive extraction of natural resources like fossil fuels, minerals, forests, and land. To tackle significant global challenges, including the consumption of natural resources, air pollution, and climate change, radical changes have been suggested over the past decades. As part of this strategic initiative, prioritizing sustainability in construction has emerged as a crucial focus in the design of all projects. In order to identify the most environmentally sustainable reinforced concrete (RC) slab system, this research investigates the carbon emissions associated with various slab systems, including solid, voided slabs and precast floor systems. The results demonstrate that beam and slab floor and solid slabs have the highest embodied carbon due to the significant use of concrete and related materials, whereas voided slabs and two-way joist floors exhibit lower carbon emissions. The results indicate that the two-way joist system is the most environmentally advantageous option. For precast floor systems, post-tensioned concrete and hollow-core slabs demonstrate the lowest embodied carbon levels. This research provides practical recommendations for architects and engineers aimed at enhancing sustainable design methodologies. It emphasizes the importance of incorporating low-carbon materials as well as pioneering flooring technologies in upcoming construction initiatives to support the achievement of global sustainability objectives.

Keywords: embodied carbon; reinforced concrete; optimization; concrete slabs; voided slabs; floor types

1. Introduction

The ability of the planet to sustain life has evidently reached a critical threshold, leading to irreversible damage to its resources, inhabitants, and ecosystems. Consequently, sustainability has emerged as a paramount global concern, prompting the proposal of transformative measures to tackle pressing issues such as the consumption of natural resources, air pollution, climate change, waste generation, and environmental degradation in urban areas. Considering this, it is imperative for the planet to reduce emissions by approximately 50% by the year 2050, as significant environmental challenges, including global warming and climate change, have been driven by carbon dioxide (CO₂) emissions and other greenhouse gases that are already impacting human existence.

It is crucial to recognize that changes must be made before the planet's finite natural resources are depleted. The enhancement of construction methodologies to mitigate detrimental environmental impacts has garnered the attention of building professionals worldwide. In alignment with this

international initiative, the UK Building Leadership Council, in conjunction with the UK Government, unveiled the Construction Industry Deal in November 2024, allocating £27 billion to facilitate the industry's transformation. While various sectors within the construction industry warrant consideration, prioritizing sustainability in the design of diverse structural components in reinforced concrete (RC) structures is essential for reducing the reliance on cement and aggregates during the construction process.

Concrete ranks as the second most utilized material globally, following water, with an estimated average consumption of 1 cubic meter per individual annually [1]. Over 30 billion tons of reinforced concrete are produced annually worldwide, with cementitious materials being responsible for 6-8% of global anthropogenic emissions [2–6]. It has been reported that in 2020 global concrete and cement production exceeded 14.0 billion m³ and 4.2 billion tons [7]. Notably, construction of buildings requires significant quantities of concrete. According to the European Ready-Mixed Concrete Organization, approximately 60% of the ready-mix concrete produced in Europe is consumed for building construction [8]. At the same time, there is an increased urgency towards designing carbon efficient concrete buildings given the current decarbonisation targets for the industry as set out as part of the European Green Deal [9]. Its significance is closely tied to infrastructure development, encompassing the construction of bridges, buildings, air and maritime terminals, and roads, among other projects [10]. The high levels of consumption can be attributed to its remarkable performance and versatility, as well as the local availability of raw materials necessary for its production [11]. The concrete production sector plays a crucial role in the economic advancement of nations, contributing to the gross domestic product (GDP) and creating job opportunities [12]. Furthermore, the concrete industry accounts for approximately 50% of the global demand for primary energy and natural resources [13], 30% of total waste generation [14], 15% of freshwater consumption [15], and 33% of anthropogenic greenhouse gas emissions [16].

Several different concrete floor solutions are available in the industry along with the design guidelines. Following BS EN 1992-1-1 [17] for the design of concrete structures, The Concrete Centre [18,19] has published design guidelines for several types of slabs mentioning relative pros and cons regarding the speed of construction, economy, ease of service distribution, story height, and potential off-site construction. Supporting optimisation of slabs, they have developed the program Concept V4: Cost and Carbon [20] which can rank the floor type in terms of either cost or embodied carbon when the column grid is input. Flat slabs, two-way spanning slabs, post-tensioned flat slabs, one-way slabs, one-way slabs on wide beams, ribbed slabs, troughed slabs, and hollow-core slabs are designed in the program, following Economic Concrete Frame Elements to Eurocode 2 [21].

In 2020, global carbon dioxide emissions surpassed 34 gigatons, translating to approximately 4.48 metric tons per individual [22]. Consequently, the concentration of CO₂ in the atmosphere rose to 417 parts per million [23,25]. The average global temperature has risen by 1.01 °C since 1880, with two-thirds of this increase occurring after 1975. This rise has prompted significant concerns regarding the loss of glaciers, changes in biodiversity, elevated sea levels, and more severe heat waves [23,25], thereby emphasizing the necessity for global carbon emission reductions [24]. The Paris Agreement of 2015 establishes long-term objectives aimed at ensuring that all countries limit the increase in global temperature to well below 2 °C, with a preference for keeping it below 1.5 °C relative to pre-industrial levels. As the construction industry increasingly prioritizes sustainability, addressing the embodied carbon in concrete structures has emerged as a critical challenge, especially as the sector strives towards low-carbon construction objectives and strategies for climate change mitigation [14]. The United Kingdom has committed to a long-term goal of achieving decarbonization across all economic sectors to reach net-zero emissions by 2050 [26].

Up to 97% of the global warming impacts are known to be from the contribution of six greenhouse gases: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆) [27]. To facilitate comparable results, CO₂ equivalent is used to measure environmental impact of the construction activities where the effects of other gases are calculated as an equivalent global warming impact as CO₂ [28]. CO₂ has

been selected as the base since it plays a major role, accounting for 77% of all greenhouse gas emissions [29].

Embodied carbon refers to the greenhouse gas emissions generated throughout the entire lifecycle of a building or infrastructure, encompassing all phases from construction to demolition [30–34]. This includes:

- Extraction and Transportation: The energy consumed in the extraction of raw materials and their transportation to the construction site.
- Manufacturing: The emissions produced during the manufacturing processes of construction materials.
- Installation: The emissions associated with the installation of these materials.
- Maintenance: The emissions resulting from the ongoing maintenance of the building.
- Demolition: The emissions generated during the demolition of the structure.
- Disposal: The emissions linked to the disposal of the building's waste.

Embodied carbon represents a substantial portion of global emissions, contributing approximately 11% to total greenhouse gas emissions worldwide. Mitigating embodied carbon emissions is crucial for combating climate change, particularly since a significant amount of these emissions occurs prior to the actual construction phase [35–39].

To assess the embodied carbon of a product, a life cycle assessment (LCA) is employed to evaluate the environmental impact at each stage of its lifecycle. The findings are typically reported in terms of carbon dioxide equivalent units (CO₂e) [3,32,40].

The production of steel and cement is the primary source of embodied emissions, accounting for 90% of emissions in typical buildings. About 8% of global emissions come from cement alone, a significant building material, primarily from its production processes [30,31]. Specifically, the production of Portland cement, a vital component that releases 0.8 to 0.9 kg CO₂ for every kilogram of clinker produced, accounts for 79% of the carbon included in concrete [2,3]. Steel, which is used for reinforcement, contributes an additional 6% to 7% of global greenhouse gas (GHG) emissions [40,41].

Concrete and steel can be responsible for 65–75% of total embodied carbon in buildings [42,43]. Furthermore, Floor systems were responsible for a share of up to 75% of the overall embodied carbon of the superstructure [44,45].

As the global community grapples with the urgent need to address climate change, the construction industry has come under increasing scrutiny for its significant contribution to greenhouse gas emissions. Understanding the factors that contribute to these embodied emissions is essential for developing effective strategies to mitigate the industry's environmental impact [46–49]. As building efficiency advancements continue to reduce operational energy demand, it is expected that embedded carbon's percentage contribution to lifecycle emissions will rise even more [3,40].

The construction industry's substantial contribution to global greenhouse gas emissions is extensively documented in the literature. Buildings and the construction industry are consistently identified as major contributors to climate change, with structures accounting for a significant portion of upfront greenhouse gas emissions [3]. A substantial body of research underscores the urgent need to address embodied carbon emissions to effectively meet internationally agreed-upon climate targets [51,52]. Furthermore, the lack of systematic comparisons between various building materials is highlighted as a significant gap in existing research [3], emphasizing the need for more comprehensive studies to inform sustainable building practices. The research consistently points toward the necessity of reducing embodied carbon emissions in the built environment to mitigate the effects of climate change [51]. In 2020, a significant portion of global CO₂eq emissions was attributed to the construction sector highlighting the urgent need for change [51].

The construction industry's embodied carbon emissions represent a significant and often overlooked aspect of its environmental impact. By understanding the factors that contribute to these emissions and implementing comprehensive strategies for their reduction, the industry can play a

vital role in the global effort to mitigate climate change and foster a more sustainable built environment [48,54,55].

The structures should be designed to meet the criteria for structural resistance, serviceability and durability [56]. For a given set of criteria for a concrete floor design, there exists a range of structural designs that meet such requirements but have different grids, element sizes, steel reinforcement design, and even shapes. From the perspective of optimisation, such alternative designs can be analysed to seek the design with minimum possible embodied carbon. Different researchers have illustrated various strategies to minimise embodied carbon in concrete floors based on parametric design [57,58], alternative analyses [44,59], and shape optimisation [60–62]

Existing design guidelines such as the IStructE Design Manual [63] and the Concrete Buildings Scheme Design Manual [18] offer span to depth ratios as the starting point for the design process of steel reinforced concrete beams. A set of beam designs to meet the same design criteria can be generated by iteratively designing for a range of sectional dimensions and reinforcement configurations. Scanning through such a design space has the potential to identify the beam design with minimum embodied carbon for the given set of design criteria. Concrete beams can be optimised by selecting the optimum sectional dimensions and reinforcement design. Therefore, such parametric design approaches are important to be considered in carbon optimisation strategies for concrete beam designs [64,65].

Shape optimisation is a proven strategy to reduce material usage by providing the necessary amount of material in the right places. Using fabric as a formwork to cast concrete beams/slabs in optimised shapes [61,66,67]. Shape optimisation using flexible formwork can reduce concrete consumption in beams/slabs by up to 44% [68].

Minimising the embodied carbon considering depth profile, width profile, flexural reinforcement and shear reinforcement simultaneously may also result in designs that are different from the outcomes of previous design methods. Therefore, shape optimisation of beams as parametric design exploration has the potential to further reduce embodied carbon in reinforced concrete beams or slabs [66].

Studies on the floor illustrate the development of optimisation algorithms by varying different design parameters. Hence, parametrically varying slab thickness, grade of concrete, column spacing, column size, and reinforcement should be integral aspects in exploring the potential of reducing embodied carbon in reinforced concrete flat slabs [57,69–71]. Parametric design of slab thickness essentially deviates from conventional span to depth ratios for deflection control unless the study is being limited by such ratios. Hence, the parametric optimisation algorithms should be coupled with another measure to account for deflection performance. In optimisation studies used the Equivalent Frame Method [69] used adjusted span-to-depth ratios according to Australian Standards (AS 3600-2018) [57], whereas for deflection control used Finite Element Models [70,71].

All these referred studies observed that the deflection criteria govern the optimum designs, especially for longer spans. Therefore, relaxing the restrictions imposed by both the conventional span-to-depth ratios and conventional deflection benchmarks may have the potential to further reduce embodied carbon in slab designs. The argument is that larger deflections could be accepted if curved shape optimized members can be accepted for the sake of reducing embodied carbon. Further research may be required in terms of approving larger deflections if such allowances can result in significant savings of embodied carbon. Hence, combining optimisation algorithms with a parametric finite element model to estimate non-linear long-term deflection can facilitate the discussion about pushing the boundaries of conventional span-to-depth ratios and conventional deflection benchmarks [72].

Various strategies to minimise embodied carbon of concrete floors can be found across literature. Different strategies require different changes to the conventional methods in design and/or construction where the effort to implement them can be different to each other. Optimization algorithms were developed to minimize the embodied carbon of concrete flat slabs by adjusting various design parameters, with the findings demonstrating applicability without requiring changes

to current construction practices for reinforced concrete flat slabs [53,57,70,71]. Various studies have compared different systems available in the market to identify the floor type with the minimum embodied carbon for specific design criteria, highlighting that implementing the findings requires adjustments during the early-stage procurement process [21,59,73]. developing novel low carbon floor systems to remove unwanted concrete by transferring loads through compressive membrane actions rather than flexure [60–62].

The construction industry plays a significant role in the global performance of not only environmental degradation but also the economy. The global construction industry values around 10 trillion USD per year, which is 13% of the world economy, as estimated by McKinsey Global Institute [27]. Global Construction Perspectives and Oxford Economics predict that the global construction market will reach 17.5 trillion USD by 2030 with an average annual growth rate of 3.9%. Therefore, Mult objective optimisation considering both cost and embodied carbon of concrete building design is of vital importance in the present context [75].

2. Significance of Research

This research addresses a critical gap in our understanding of how different floor types in concrete structures contribute to embodied carbon emissions, a crucial consideration as the construction industry strives to meet ambitious carbon reduction targets. With buildings and construction accounting for a significant portion of global greenhouse gas emissions, and floor systems responsible for up to 75% of the superstructure's embodied carbon, there is an urgent need to evaluate and compare the environmental impact of various concrete slab systems. This study's systematic comparison of different floor types, including flat slabs, beam and slab systems, ribbed slabs, waffle slabs, post-tensioned slabs, hollow-core slabs, and innovative designs like Nervi-style and arched slabs, provides valuable insights for architects and engineers seeking to minimize the carbon footprint of their projects.

The significance of this research extends beyond mere environmental considerations to encompass practical implications for the construction industry. As governments worldwide implement stricter regulations on carbon emissions and the industry faces increasing pressure to adopt sustainable practices, understanding the embodied carbon implications of different floor systems becomes essential for informed decision-making. This study's comprehensive analysis of various floor types, considering factors such as material efficiency, structural performance, and carbon emissions, provides practitioners with crucial data to optimize their designs for both environmental and structural performance.

3. Life Cycle Assessment

Life Cycle Assessment is often used to quantify the environmental impact of construction works [77–83]. Life Cycle Assessment is defined as a methodological framework to estimate and evaluate the environmental impact of a product or a process, considering the whole product life cycle [74,110]. BS EN 15978 [84] and BS EN ISO 14044 [85] has standardised the calculation methods for the assessment of the environmental performance of buildings by defining the phases of the life cycle (Figure 1), as below:

- Modules A1–A3 (Product Stage): Emissions from material extraction, processing, and manufacturing.
- Module A4 (Transport): Emissions from transporting materials to the site.
- Module A5 (Construction): Emissions during assembly and on-site activities.
- Modules B1–B7 (Use Stage): Emissions from maintenance, repair, and replacement during the building's operational life.
- Modules C1–C4 (End-of-Life): Emissions from demolition, transportation, and disposal.
- Module D (Beyond Lifecycle): Potential benefits from material reuse or recycling.

Due to the significance of the present climate emergency, CO2 equivalent emissions and consumption of energy have been widely used as indicators for environmental impact assessment of buildings [28,33,86–94]. The Inventory of Carbon and Energy by Circular Ecology suggests that CO2 equivalent emissions can be considered a more representative measurement of the environmental impact [95].

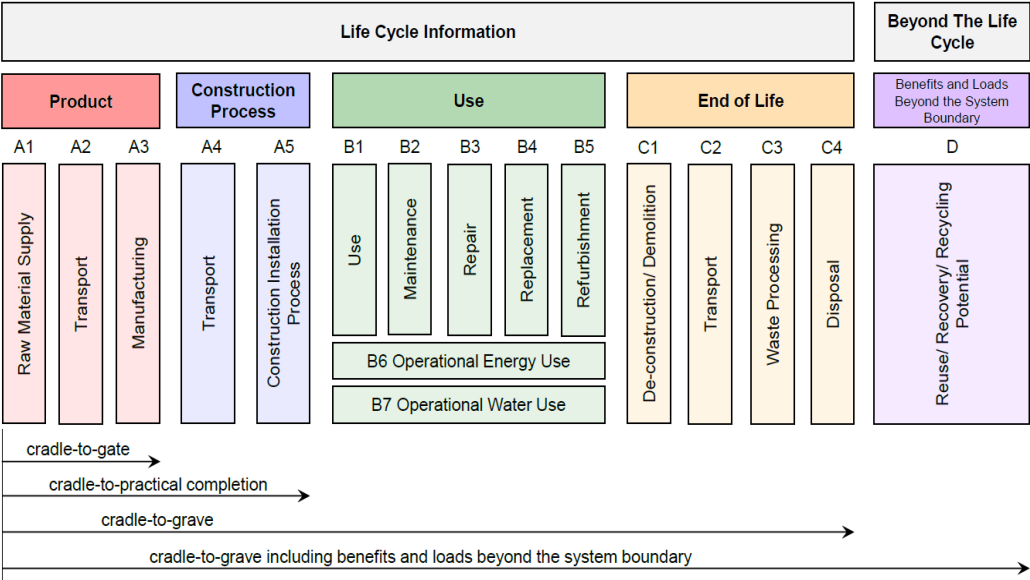


Figure 1. Life Cycle Information for Buildings according to BS EN 15978 [84].

In concrete structures, the product stage—also referred to as "cradle-to-gate"—is the most carbon-intensive due to raw material extraction and cement manufacturing [84]. Studies suggest that 50-75% of the embodied carbon in a building can be attributed to this stage [33]. As a result, reducing the embodied carbon in concrete structures requires significant intervention during the early design and material selection phases [32].

3.1. Life Cycle Assessment Methodology

Life Cycle Assessment (LCA) is an analytical framework that evaluates the environmental impacts of a product or service throughout its entire life cycle, encompassing all stages from raw material extraction to production, use, and end-of-life disposal. The methodology is grounded in the principles of systems thinking and aims to provide a comprehensive view of the environmental burdens associated with a product [96,97]. The LCA process is typically divided into four distinct phases:

3.1.1. Goal and Scope Definition

This initial phase involves identifying the purpose of the assessment, the intended audience, and the specific questions to be answered. It also includes defining the system boundaries, which delineate what is included in the assessment (e.g., materials, processes, transportation) and what is excluded [98].

3.1.2. Inventory Analysis (LCI)

In this phase, data is collected on the inputs and outputs of the system being studied. This includes quantifying energy use, raw material consumption, emissions into air, water, and soil, and waste generation. The inventory analysis is often data-intensive and may require the use of databases and software tools to compile relevant information [28,99].

3.1.3. Impact Assessment (LCIA)

The third phase evaluates the potential environmental impacts associated with the inputs and outputs identified in inventory analysis. This may involve categorizing impacts into various environmental issues such as global warming potential, ozone depletion, acidification, and resource depletion. Various impact assessment methods exist, including Eco-indicator, CML, and TRACI, each with its own set of indicators and methodologies [100].

3.1.4. Interpretation

The final phase involves analyzing the results of the inventory and impact assessment to draw conclusions and make recommendations. This phase often includes sensitivity analysis to understand how changes in assumptions or data can affect outcomes, as well as a critical review to ensure the robustness of the findings.

3.2. Embodied Carbon Assessment

Embodied carbon refers to the total greenhouse gas emissions (GHG) associated with the lifecycle of building materials, including extraction, manufacturing, transportation, installation, maintenance, and end-of-life disposal. It is increasingly recognized that embodied carbon can account for a substantial share of a building's total carbon emissions, particularly in the context of energy-efficient buildings where operational energy use is minimized. Research indicates that embodied carbon can represent up to 80% of a building's total lifecycle emissions, especially in structures with low operational energy requirements [67–96].

The assessment of embodied carbon typically involves the use of Life Cycle Assessment (LCA) tools and databases that provide embodied carbon factors for various materials. These factors are derived from extensive research and data collection, reflecting the emissions associated with the entire lifecycle of each material. For instance, materials such as concrete and steel have high embodied carbon factors due to energy-intensive production processes, while sustainably sourced timber may have a lower embodied carbon footprint [98,99].

Moreover, the assessment process must consider the context of material use, including transportation distances, construction practices, and the potential for recycling or reuse at the end of the material's life. By integrating embodied carbon assessments into the design and decision-making processes, architects and builders can make informed choices that significantly reduce the environmental impact of their projects [28,100].

3.3. Embodied Carbon Calculations

The embodied carbon factor is a crucial metric that quantifies the carbon emissions associated with a specific unit of material or product, typically expressed in kilograms of CO₂ equivalent per kilogram of material (kg CO₂e/kg) [Table 1]. This factor is essential for calculating the total embodied carbon of a building or infrastructure project, as it allows for the aggregation of emissions across various materials used in [96,97].

Different materials exhibit varying embodied carbon factors, influenced by factors such as production methods, energy sources, and transportation distances. For example, the embodied carbon factor for concrete can range from 100 to 300 kg CO₂e/kg, depending on the mix design and production processes, while steel can have an embodied carbon factor exceeding 1,000 kg CO₂e/kg [98,99]. Conversely, sustainably sourced timber may have an embodied carbon factor as low as 50 kg CO₂e/kg, making it a more environmentally friendly option when considering carbon emissions [28].

The choice of building materials is a significant driver of embodied carbon, as the manufacturing processes for materials like steel, concrete, and aluminum are highly energy-intensive and often reliant on fossil fuels. Design decisions made by architects and engineers, such as the selection of building systems and the optimization of material quantities, also play a crucial role in determining the overall embodied emissions of a project [47,48].

Understanding these factors is critical for stakeholders in the construction industry, as it enables them to evaluate the carbon implications of material choices. Furthermore, the embodied carbon factor can be influenced by innovations in material production, such as the use of alternative binders in concrete or the adoption of low-carbon steel production techniques [100].

Embodied carbon is calculated using lifecycle assessment (LCA) methodologies, integrating data for each module. For accurate results, environmental product declarations (EPDs) and emission factors are employed. The generalized formula for embodied carbon in each lifecycle stage is [32]:

$$EC_{total} = \sum (Material\ Mass \times Carbon\ Factor_{Module})$$

(1)

Calculating the embodied carbon in concrete structures involves a systematic approach that encompasses the entire lifecycle of the material, from raw material extraction to production, use, and end-of-life disposal or recycling. To accurately assess the embodied carbon, one must first gather data on the quantities of materials used in the concrete mix, including cement, aggregates, water, and any supplementary cementitious materials (SCMs) such as fly ash or slag. Each of these components has an associated carbon footprint, typically expressed in kilograms of CO2 equivalent per unit of material [103].

The next step involves calculating the carbon emissions associated with each material. This can be done using established databases or tools that provide embodied carbon coefficients for various materials. The carbon footprint of reinforced concrete can be substantial, and using alternative materials or reducing cement content can lead to significant reductions in embodied carbon [104]. Additionally, the use of recycled aggregates can also mitigate emissions, as they typically have a lower embodied carbon compared to virgin materials [105].

Table 1. Comparison of typical embodied energy and carbon values for a variety of engineering materials [95,101,102].

Material	Embodied carbon [kgCO ₂ e/kg]
Concrete constituents	
Portland cement*	0.912
Fly ash*	0.008
GGBS*	0.083
Aggregate*	0.00747
Water*	0.0008
Superplasticiser‡	1.88
Concrete example mixes (CEM I)	
C20/25*	0.121
C32/40*	0.149
C40/50*	0.172
Metals	
Steel reinforcement*	1.99
Hot-rolled steel section*	1.55
Galvanised steel sheet*	2.76
Aluminium extrusions*	6.83
Fibre materials	
Carbon fibre†	20.3
Aramid fibre†	17.3
Glass fibre†	3.00
Basalt fibre†	0.057
Fibre composite matrix materials	
Epoxy†	6.60
Vinyl ester†	4.31
Polyester†	2.54

*Source: Jones and Hammond (2019)

†Source: Granta Design Ltd. (2018)

‡Source: EFCA (2015)

Lifecycle assessment (LCA) methodologies are crucial in this context. They allow for a comprehensive evaluation of the environmental impacts associated with all stages of a concrete structure's life. This includes not only the production phase but also transportation, construction, maintenance, and end-of-life scenarios such as demolition and recycling [109]. Studies have shown that Incorporating carbonation effects, where concrete absorbs CO₂ from the atmosphere over its service life, can help offset emissions. Estimates suggest that carbonation can reduce approximately 11% of the total emissions associated with ordinary Portland cement concrete [106].

Furthermore, the design of concrete structures can significantly influence their embodied carbon. Strategies such as optimizing the mixed design, reducing the amount of cement, and utilizing low-carbon alternatives can lead to substantial reductions in embodied carbon [107]. For instance, using thin-shell structures has been proposed as a method to reduce the embodied carbon of concrete buildings while maintaining structural integrity [108].

3.4. Uncertainty in Estimation of Embodied Carbon

Life cycle assessment of buildings can be approached in various methods where each method has its own challenges and potential uncertainties. Several studies [28,76,78] reviewed available methods of life cycle analysis and categorised them as statistical analysis, process-based analysis, economic input-output analysis and hybrid analysis. They further explained that the bottom-up process-based assessments deliver more accurate and reliable results but can be time-consuming and costly whereas top-down input-output analyses cannot adequately project specific differences [110,111].

Various databases are available with data for embodied carbon for common construction materials. Various studies have reviewed methods for estimating embodied carbon in buildings, emphasizing that the available databases for carbon coefficients encompass different life-cycle boundaries. These databases are derived from sources such as existing literature, manufacturing reports, environmental product declarations, process-based analyses, and economic input-output analyses [112–114].

Organisations such as RICS [115], UK Green Building Council [116] and IStructE [32] have developed detailed guidelines to calculate embodied carbon in buildings along with the benchmarks. Therefore, estimating embodied carbon of buildings in the scope of an optimization study as an objective function can be approached by referring to an available database for embodied carbon coefficient of each building material.

Values for each construction material are needed to quantify embodied carbon of structural designs as the objective function in optimisation studies. Since the shares of embodied carbon from different construction materials in a building design depend on the adopted carbon coefficients, designs with minimum embodied carbon can also depend on the adopted coefficients. While there are numerous sources for embodied carbon values for different construction materials, uncertainties are inevitable.

Embodied carbon has its inherent complexity due to that being primarily a function of materials, products, systems, and technologies used in the construction of buildings [112,117,118]. Embodied carbon coefficients should be generally considered tentative; Therefore, embodied carbon is to be calculated with the understanding of the potential deviations [33].

Numerous factors contribute to the ambiguity of embodied carbon coefficients. Unique characteristics can be a significant barrier when comparing building designs with different objectives, materials, designs, and locations [74,113]. It has been further explained that considering building layers, such as substructure, superstructure, facade, finishes, and services, can create challenges in making comparisons across different studies. [112] As far as the building materials are concerned the possible variations of carbon values can be due to differences in calculational methods, geographical location, energy composition, data source, manufacturing technology, temporal representation, and economic complexities [33,76,89,111,117,119]. Therefore, the uncertainty of the adopted carbon coefficients should also be considered in developing optimisation algorithms for concrete floors designs [14,112].

The ratio of carbon coefficients of concrete to steel from several sources ranged from 0.0208 to 0.4545, and illustrated how the details of the optimum design vary accordingly [120]. The uncertainty of embodied carbon estimations has been modeled, revealing that values can range from 50% to 140% of the original results at the extremes of a Monte Carlo simulation [121]. Figure 2 illustrates their outcome, for an example study of a building, shown by construction materials [121]. The average embodied carbon of C28/35 concrete is 0.126 kgCO₂e/kg as per The Inventory of Carbon and Energy by the Circular Ecology [95]. The value can be increased to 0.136 kgCO₂e/kg when only CEM I is used or decreased to 0.099 kgCO₂e/kg when fly ash is used for 40%. While the world average embodied carbon of steel rebar is 1.99 kgCO₂e/kg, using 85% recycled steel will reduce the coefficient to 1.20 kgCO₂e/kg according to the same source [95].

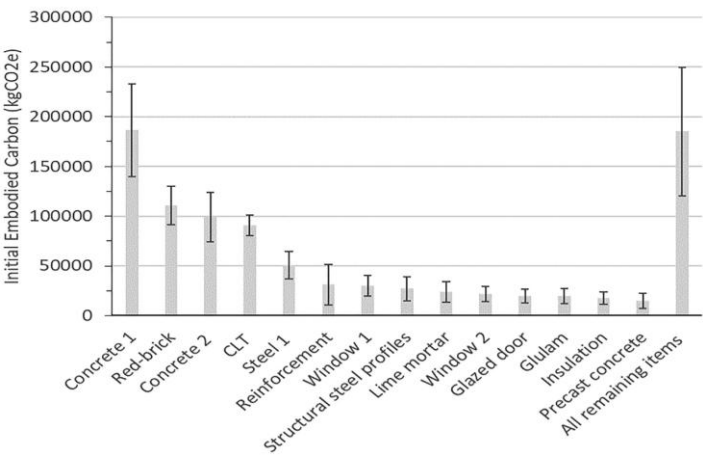


Figure 2. Uncertainty of embodied carbon by construction products [121].

4. Embodied Carbon Mitigation Strategies in RC Structures

Embodied carbon in buildings can be reduced through different strategies identified by different researchers. Four strategies to reduce embodied carbon through improved material efficiency include: (1) using longer-lasting products, (2) adopting modularization and remanufacturing, (3) reusing components, and (4) designing products with reduced material usage [122]. Methods to minimize embodied carbon have been reviewed, identifying 17 strategies that include using low-carbon materials, optimizing design, reducing, reusing, or recovering carbon-intensive materials, utilizing locally sourced materials, implementing efficient construction processes, and adopting off-site manufacturing techniques [14]. Proposing effective approaches such as using alternative materials, substituting production materials, minimizing excess through improved design and manufacturing, reusing and recycling components, and promoting adaptive reuse and life extension of existing structures. These methods demonstrate that reducing embodied carbon encompasses a wide range of strategies applicable to different phases of a building's life cycle [123–125].

Methods of minimising embodied carbon in the building were extensively reviewed in Annex 57 Subtask 4 by the Energy in Buildings and Communities Programme of the International Energy Agency (IEA EBC) [126]. The annexe divided low carbon strategies into three categories, (1) Reduction of amount of needed materials throughout entire life cycle, (2) Substitution of traditional materials for alternatives with lower environmental impacts, and (3) Reduction of construction stage impact (Figure 3) [126,127].

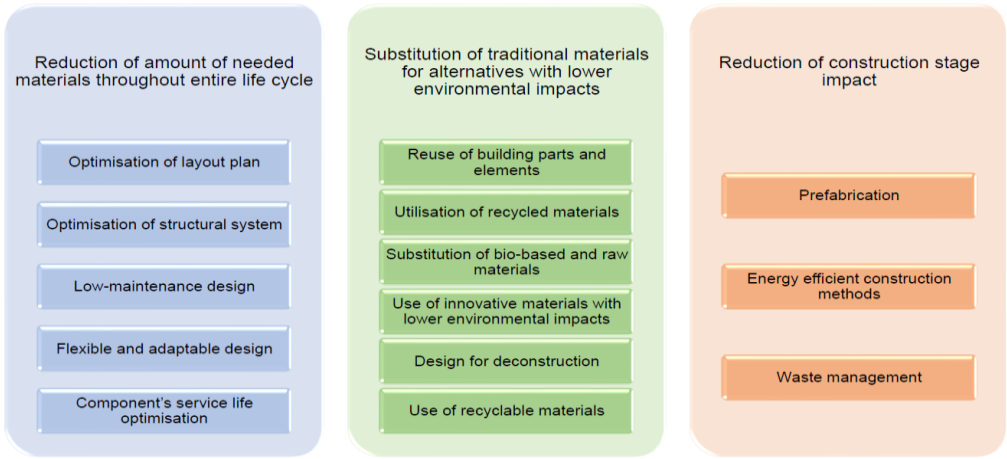


Figure 3. Various design strategies to reduce embodied carbon in buildings, IEA [126].

Research on reducing embodied carbon in buildings focuses on material efficiency, lightweight construction, and reusing components. Studies explore low-carbon binders, supplementary cementitious materials, and recycled aggregates for concrete, alongside bio-based materials and optimized designs to minimize life cycle carbon intensity and improve construction efficiency [128–131]. However, the sectors producing the by-products such as fly ash and blast furnace slag are expected to transform into low carbon alternatives, reducing the availability of supplementary cementitious materials to meet the demand for cement [132]. The discussions about reducing the embodied carbon of steel have revolved around recycling and decarbonizing the steel production process [133–135]. The studies that scrutinised the carbon emissions during the construction phase have highlighted the importance of local sourcing, minimising waste, and energy conservative construction methods [28,117,126].

Despite the climate crisis, the construction industry resists low-carbon techniques due to institutional, economic, technical, and perceptual barriers [136]. Research highlighted that ease of construction is often prioritized over material efficiency, emphasizing the importance of aligning incentives to effectively reduce carbon emissions [137]. A survey on the drivers and obstacles to low-carbon design in school buildings highlighted the complexity of building systems and the perception of higher costs as common barrier [138]. An industry survey highlights economic, legislative, cultural, knowledge-based, and geographical barriers to low-carbon methods. Evaluating embodied carbon savings against required design and construction modifications is key for informed decision-making [139].

Several efforts have been made to provide insights into pathways for reducing embodied carbon of concrete construction [140,141]. Efforts to reduce embodied carbon in concrete focus on lowering Portland cement clinker content. Additionally, optimizing design aspects, such as parametric design and structural system selection, can significantly cut embodied carbon, with studies showing a 20% reduction in flat slabs [31,142]. However, which slab structural system is the most efficient in terms of materials use remains unclear.

At the same time, design practices for reinforced concrete buildings varies across different countries, as shown in [143] where statistically significant variations in both regulated and cultural engineering practices were observed. While design of concrete buildings has been shown to result in higher masses of material needed for the structural frame compared to steel or timber solutions as per [144] it is important to identify influential design parameters that define the embodied carbon of a building. Design assumptions and conditions, such as design loads, column spacing, floor to ceiling height and slab design strength can affect the embodied carbon of a concrete building. Such parameters fall under structural design and therefore, structural design optimisation for concrete frames [45], beams [35,145,146], floors [108,147,148] have been researched as a strategy to reduce the environmental impact of concrete structures. Benefits have also been demonstrated from efficiently designing conventional floor systems towards embodied carbon reduction and materials efficiency in addition to non-conventional geometry optimisation [133,149–151]. For example, adoption of post-tensioned voided floor plates can result in up to 51% less embodied carbon of the slab system compared to a conventional flat slab [148] whilst reducing the amount of material in the concrete floor system can have a significant effect towards reducing the required size of columns and foundations [152].

Efforts have also been made to develop means for quantification of the effects of the design assumptions and conditions on the embodied carbon of buildings. For example, an analytical method was developed for understanding the environmental impact of different wall designs in [153] and statistical analysis was performed to identify the effects of construction materials on the environmental impacts of different design decisions [154]. Analytical models towards predicting the embodied carbon of structural systems were proposed in considering variations in span and applied loads for reinforced concrete flat plates and one-way slabs [144]. A study on various floor systems, including reinforced and post-tensioned designs, developed design-assisting equations to predict embodied carbon. These equations consider a concrete mix global warming potential, structural

parameters, loads, and deflection limits [155]. Embodied carbon and cost models were used to optimize reinforced concrete, steel, and timber structures. Grid and frame types had the greatest impact on cost and carbon, while alternatives like thin concrete shells offered savings. Further research is needed on structural system effects, including concrete mix variations and design parameters, to enhance material efficiency in reinforced concrete buildings [156].

Currently there appears to be unexploited potential regarding embodied carbon savings and structural system selection and optimisation, particularly in reinforced concrete buildings [3,112,157]. Therefore, there is a growing need to better understand potential reductions in embodied carbon and material use in reinforced concrete frames. This study explores design optimization and improved concrete specifications to achieve these reductions, aligning with decarbonization roadmaps for the concrete industry [158]. This also resonates with structural carbon reduction hierarchies which promote demand reductions before changes to specifications [159].

It is noted that the industry currently relies heavily on GGBS and FA for reducing the embodied carbon of concrete, through replacing large quantities of Portland cement with such materials [6,160,161]. These are constrained resources for reducing the embodied carbon on concrete [162]. Achieving large-scale decarbonization benefits of GGBS and fly ash requires further advancements in cement and concrete technology. This study primarily considers GGBS, fly ash, and limestone filler as lower-carbon supplementary cementitious materials (SCMs) due to their current availability. However, the supply of fossil fuel-based SCMs varies geographically, highlighting the need for the industry to transition to more sustainable alternatives like calcined clays [163–165]. CO₂ mineralised binders and others. These alternative binders and SCMs, should result in similar or greater embodied carbon reduction of concrete as with GGBS and fly ash [166].

4.1. Material

Some researchers have optimized concrete and steel properties, sectional dimensions, and reinforcement design to reduce embodied carbon. A study on flat slabs with varying thicknesses and column grids highlighted that reducing spans significantly lowers embodied carbon. Designs with minimal embodied carbon often approach the minimum feasible slab thickness, limiting trade-offs between slab depth and reinforcement quantity [75]. Two-way span slabs were optimized for various span lengths by adjusting slab thickness, concrete grade, and the quantity and strength of reinforcement, utilizing genetic algorithms [167]. They observed that the designs with optimum carbon had less concrete and lower strength steel than conventional designs, but the optimum designs were dominated by limiting slab thickness. This further certifies the importance of understanding the trade-off between the amount of steel and concrete chosen in a design.

Carbon reductions are possible by either adopting a lower amount of high strength concrete or adopting higher usage of cement substitutions [168]. Both strategies were identified as effective measures which can reduce embodied carbon by up to 30% and 15% respectively, but the possibility of improving mechanical properties with cement substitution was also highlighted. 10% reduction in embodied carbon was achieved by upgrading the concrete grade in a shear wall structure to a higher grade [169]. The higher durability of high-strength concrete was incorporated into lifecycle assessments, emphasizing its potential to extend the lifespan of structures [170]. Further, they illustrated the possibility of reducing embodied carbon by reducing the amount of concrete and steel by adopting high strength concrete. Ontology and semantic web rules were applied in knowledge-based systems to optimize embodied carbon in structural designs, with a case study focusing on columns [171].

Different designs of steel-reinforced concrete composite columns were compared by varying column dimensions, steel section shapes, and material strengths. [172] Contrary to other studies, researchers found that effective carbon reduction strategies depend on design loads. Increasing column dimensions benefits lower loads, while adjusting steel shape is more effective for higher loads. Steel-concrete composite columns were shown to be more efficient than reinforced concrete columns. Additionally, heuristic optimization algorithms were used to optimize precast prestressed

concrete U-beams by varying geometry, reinforcement configuration, and material properties across different spans [173].

A significant body of research focuses on material selection as a primary strategy for minimizing embodied carbon in buildings [174–176]. This section will explore various strategies employed to reduce embodied carbon throughout the entire building lifecycle, encompassing design optimization, material substitution, and effective end-of-life management. Design optimization techniques, such as parametric design, are increasingly employed to reduce material use and minimize embodied carbon [31,70,142]. Parametric design allows for the exploration of a wide range of design options, enabling the identification of designs that optimize both structural performance and embodied carbon [31,142]. The use of genetic algorithms for design optimization is also explored in the literature [70,177], demonstrating the potential of computational methods to improve the efficiency of the design process. Material substitution, replacing high-embodied carbon materials with lower-carbon alternatives, is another key strategy [174,178,179]. The use of mass timber as a substitute for steel and concrete is gaining increasing attention [51,174,179], with studies demonstrating its potential for significant embodied carbon reductions [51]. However, the limited availability and scalability of some eco-friendly options remain a challenge [180], highlighting the need for further research and development in this area. The use of supplementary cementitious materials (SCMs) in concrete is also explored as a means of reducing embodied carbon [81,189,190], and the potential of alkali-activated materials (AAMs) is examined [181].

Table 2. Effect of fly ash replacement for Portland cement on embodied carbon of concrete [28].

Concrete Grade	Embodied Carbon (kg CO ₂ -e/kg)		
	Cement Replacement with Fly Ash (%)		
	0%	15%	30%
RC 20/25 (20/25 MPa)	0.132	0.122	0.108
RC 25/30 (25/30 MPa)	0.14	0.130	0.115
RC 28/35 (28/35 MPa)	0.148	0.138	0.124
RC 32/40 (32/40 MPa)	0.163	0.152	0.136
RC 40/50 (40/50 MPa)	0.188	0.174	0.155

End-of-life management strategies, such as material reuse and recycling, are crucial for minimizing the overall environmental impact of buildings [142]. The importance of considering the entire lifecycle of building materials, from extraction to disposal, is emphasized [175], highlighting the need for a holistic approach to embodied carbon reduction. The potential for carbon sequestration in timber structures is also discussed [51,182,183], highlighting the advantages of using wood as a building material. The use of lightweight panels as an alternative to masonry walls is also investigated [175], demonstrating the potential for reducing embodied carbon through material optimization. The use of thin-shell floors as a low-carbon alternative to conventional floor slabs and beams is explored [31,108].

Fly ash, a by-product of coal combustion in power plants, has proven to be an effective partial replacement for Portland cement. Replacing 15-30% of Portland cement with fly ash reduces CO₂ emissions while improving concrete’s long-term strength, durability, and resistance to chemical attack. Additionally, fly ash reduces permeability, leading to enhanced structural performance and a smaller environmental footprint [185,186].

Similarly, Ground Granulated Blast Furnace Slag (GGBFS), derived from steel production, offers a sustainable solution by replacing up to 70% of Portland cement. GGBFS not only reduces the carbon footprint of concrete but also enhances workability and lowers the heat of hydration, making it ideal for mass concrete applications. Furthermore, its incorporation improves the resistance of concrete to sulfate attack, increasing its long-term durability and sustainability [187,188].

Natural pozzolans, including volcanic ash, serve as another effective alternative for reducing the reliance on Portland cement. These materials improve concrete’s mechanical properties, reduce

permeability, and mitigate alkali-silica reaction (ASR), which is a common issue in moisture-exposed structures. The use of natural pozzolans has been shown to significantly lower the environmental impact of concrete production [189,190].

Innovative materials such as geopolymers, formed through the reaction of aluminosilicate materials with alkaline solutions, provide a promising low-carbon alternative to traditional cement. Geopolymers achieve comparable or superior mechanical performance while significantly reducing embodied carbon. Their production consumes less energy and utilizes industrial by-products, including fly ash and slag, as raw materials. Studies demonstrate that geopolymers exhibit high compressive strength and exceptional durability, making them a viable solution for sustainable construction [191,192]

Finally, the incorporation of Supplementary Cementitious Materials (SCMs), such as silica fume and rice husk ash, further advances the sustainability of concrete. These materials enhance mechanical properties, improve durability, and reduce embodied carbon by up to 50%, depending on the proportion of cement replaced and the type of SCM used. The integration of SCMs not only reduces the environmental impact of concrete production but also extends the lifespan of concrete structures [193,194].

Table 3. Emission Factors of Ready-mixed Concrete, EFi [195].

Concrete mix with/without cement substitute ^a	Emission factor for each strength class (kg CO ₂ -e/m ³)					
	C30	C40	C50	C60 ^b	C70	C80
100% Cement	295 ± 30 ^c	335 ± 30	365 ± 20	402 ± 27	437 ± 27	471 ± 27
65% Cement + 35% FA	200 ± 19	227 ± 19	265 ± 13	271 ± 17	293 ± 17	316 ± 17
25% Cement + 75% GGBS	108 ± 9	120 ± 9	130 ± 6	141 ± 8	152 ± 8	163 ± 8

^a In order to evaluate the maximum possible reduction of carbon emissions, the maximum substitution rates of FA and GGBS are considered in the analysis. ^b Because minimum cementitious binder contents and strength classes have a linear relationship, the emission factors for C60, C70, C80 can be extrapolated from the literature data. ^c The range is due to the change of maximum aggregate size in concrete mix design. The average values are adopted in the analysis.

4.2. Structural Optimization

Parametric design has become a valuable tool for optimizing both the structural performance and environmental impact of concrete structures. Parametric modeling allows designers to vary multiple parameters—such as slab thickness, reinforcement details, and concrete grade—to find the most efficient design solution. Research has shown that optimizing slab thickness and column grid layout can effectively reduce both material usage and embodied carbon [57,58]. Building Information Modeling (BIM) integrated with parametric tools has been employed to optimize concrete flat slabs, achieving a 10-15% reduction in embodied carbon by minimizing slab thickness and increasing column density [69]. Similarly, reducing slab thickness through parametric optimization has been found to lower the embodied carbon of flat slabs by up to 15%, while maintaining structural integrity [58].

The grade of concrete used in a structure directly influences its embodied carbon. Higher grades of concrete, such as C40/50, offer greater strength and allow for thinner sections, but they are associated with higher carbon emissions due to their higher cement content. A study on flat slabs found that using lower grades of concrete, such as C20/25, reduced embodied carbon by up to 12% for shorter spans [71]. However, the choice of concrete grade must balance the environmental benefits with structural performance, as higher-grade concrete may be necessary in long-span or high-load applications to ensure durability and safety. This trade-off highlights the importance of selecting the appropriate concrete grade based on the specific requirements of the project [14].

Steel reinforcement is another major contributor to the embodied carbon of concrete structures due to the high energy intensity of steel production. Steel can account for 20-25% of the total embodied carbon in a typical reinforced concrete structure [118]. One way to reduce this impact is to optimize the amount and placement of steel reinforcement within the structure. For example, increasing reinforcement in specific areas of high stress can allow for thinner concrete elements, reducing the overall volume of concrete used and, consequently, the embodied carbon [69]. However, increasing steel reinforcement can also offset these gains due to the high carbon intensity of steel. This trade-off needs to be carefully managed to ensure that the overall carbon footprint is minimized.

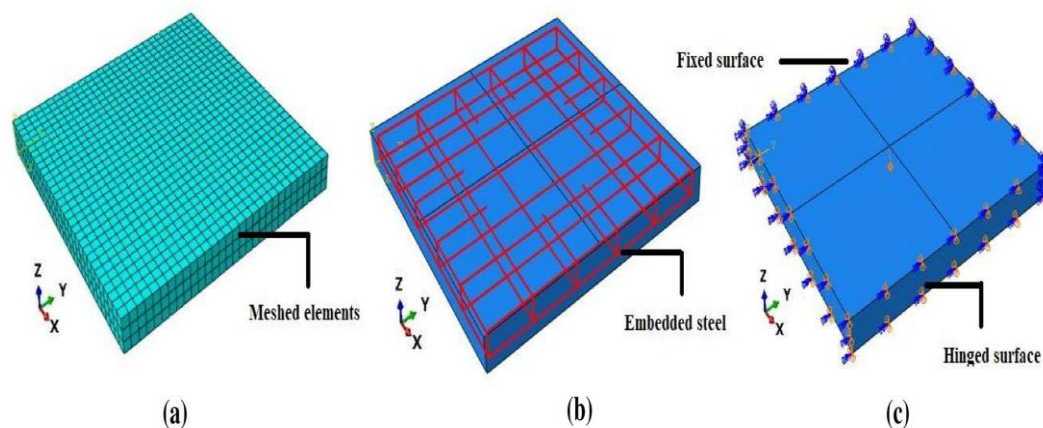


Figure 4. Geometry and boundary conditions of the finite element model of the two-way slab (a) meshing (b) embedded region constraint (c) boundary conditions [2].

The possibility of optimising concrete elements by considering a range of sectional dimensions and reinforcement designs according to an existing design code has been studied by several researchers. Developing a set of design charts for concrete frame elements and listing the slab depths which give the minimum cost for each span, based on a series of parametric designs [21]. Controlling the deflections of their designs referring to BS EN 1992-1-1 [17] adjusted span-to-depth ratios, they also found that providing more reinforcement to further reduce the allowable slab thickness can reduce overall cost. A review of efforts to optimize the cost of reinforced concrete members highlighted the uncertainties associated with defining the cost function, as well as the fuzziness and variability in selecting appropriate cost parameters [196].

The optimization of steel-reinforced concrete frames or beams through adjustments in reinforcement arrangement and sectional dimensions was demonstrated using genetic algorithms [64,65,197]. With the proven savings of around 25 to 36%, their studies confirm that understanding the trade-off between sectional dimensions and reinforcement may be a promising approach to optimised embodied carbon of concrete members. The optimization of T-shaped one-way slabs was demonstrated by generating over a million solutions through variations in sectional dimensions and reinforcement design, utilizing a heuristic algorithm [198]. Reinforced concrete box bridge frames were designed by varying the geometry of the box beam and reinforcement configuration using heuristic optimization algorithms. The study highlighted the impact of deflection and fatigue limits on the resulting optimal designs [199]. A parametric variation of beam geometry and reinforcement quantity was conducted to identify optimal designs, revealing a parabolic relationship between depth and embodied carbon. This finding supports the effectiveness of the parametric design approach for optimization [35].

Structural optimization aims to minimize material usage while ensuring safety, performance, and cost-effectiveness, offering a viable pathway to reducing the embodied carbon of reinforced concrete (RC) structures. Advanced computational tools, such as finite element analysis (FEA), enable precise modeling of structural behavior, allowing engineers to identify optimal material distributions [200]. This approach facilitates targeted material use, reducing concrete consumption without compromising structural integrity. Recent advancements in FEA have further enhanced its ability to

predict structural performance under various loading conditions, contributing to more efficient and sustainable designs [201]. The integration of FEA into lifecycle assessments (LCA) allows for the evaluation of embodied carbon across design alternatives, ensuring sustainability-focused decision-making [184,193]. Machine learning techniques have also been integrated into FEA workflows, streamlining the design process and enabling the rapid identification of low-carbon solutions [202,203].

Structural optimization techniques also include topology optimization, which determines the optimal material layout within a given design space under specific constraints [204]. This method leads to innovative designs that maximize structural performance while minimizing material use [205]. High-strength concrete is another effective strategy, enabling smaller cross-sections and reducing overall concrete volume while enhancing load-carrying capacity [206]. Additionally, composite materials, such as carbon fiber-reinforced polymers (CFRP), improve the strength-to-weight ratio of structural components, allowing for reduced concrete usage and increased durability, particularly in dynamic loading conditions [207,208]. The adoption of precast concrete elements further contributes to material efficiency, as these components are manufactured under controlled conditions, reducing waste and optimizing material use for specific load requirements [209,210].

Research demonstrates that these techniques collectively reduce the embodied carbon of RC structures by 20-30% [211]. Case studies highlight their practical application, including material savings in bridge design [209] and precast concrete systems [213].

4.3. Deflection Management

Effective management of deflection in reinforced concrete (RC) structures is critical for ensuring serviceability, durability, and sustainability. One approach involves utilizing high-performance concrete with enhanced tensile strength, which reduces deflections under service loads. This type of concrete is designed for superior durability, workability, and strength, helping to mitigate deflection and cracking issues. Research has demonstrated that high-performance concrete significantly improves the serviceability of structures by limiting deflection and enhancing long-term performance [47,214].

The addition of fibers, such as steel or synthetic materials, to concrete further contributes to deflection management. Fiber reinforcement improves the post-cracking behavior of concrete by enhancing ductility, energy absorption, and toughness. It also helps control cracking, making the material suitable for applications requiring high seismic resilience. Studies indicate that fiber-reinforced concrete exhibits superior performance under load and is effective in reducing deflections and extending structural lifespan [215,216].

Pre-stressing techniques are another effective strategy for managing deflections. By introducing compressive forces into concrete elements, pre-stressing counteracts deflections caused by service loads, enabling longer spans and more efficient material use. Methods such as pre-tensioning and post-tensioning have been shown to significantly enhance the load-carrying capacity of beams and slabs, reducing deflections and improving overall structural performance [217,218].

The use of real-time monitoring systems provides valuable data for assessing and managing deflections throughout a structure's lifecycle. Technologies such as fiber optic sensors and wireless systems allow for continuous assessment of structural health. These advancements enable timely interventions and maintenance, which extend the lifespan of structures and improve overall performance. Recent research highlights the efficacy of real-time monitoring in optimizing maintenance strategies and ensuring long-term serviceability [203,219].

Adjustments in structural design also play a significant role in managing deflections. Techniques such as increasing beam depth or introducing camber in slabs account for anticipated deflections during the design phase, enhancing the serviceability of structures. Studies have shown that these design adjustments minimize material usage while maintaining performance, contributing to more sustainable construction practices [220,221].

4.4. Voided Floor Systems

Voided floor systems offer an innovative solution for reducing material usage in concrete slabs while maintaining structural performance. By incorporating voids or openings within the slab, these systems achieve significant reductions in material consumption and embodied carbon. Research shows that voided slabs can reduce concrete usage by up to 30%, resulting in substantial material cost savings without compromising structural integrity [222]. The lighter weight of these slabs also reduces the overall load on the structure, contributing to more efficient designs [223].

In addition to material savings, voided systems enhance the thermal insulation properties of buildings, improving energy efficiency. The voids reduce heat transfer, leading to lower energy consumption for heating and cooling, which in turn reduces the building's carbon footprint. Studies have demonstrated that buildings with voided floor systems achieve improved energy performance and reduced operational costs [224,225].

The use of prefabricated voided floor systems accelerates construction schedules by enabling off-site manufacturing. Prefabrication minimizes on-site waste, improves quality control, and reduces labor costs. Recent advancements in these systems highlight their potential to streamline construction processes while maintaining high-quality outcomes [226,227].

Another advantage of voided systems is their adaptability to various architectural designs, enabling creative and sustainable building solutions. Their versatility makes them suitable for residential, commercial, and industrial applications. Research highlights the integration of voided floor systems into diverse architectural styles, promoting both aesthetic appeal and sustainability [222,228].

Non-extractable void formers, such as those made from polystyrene foam, further enhance the efficiency of voided slabs. These formers are integrated into the slab design to reduce concrete usage while preserving structural integrity. Studies indicate that non-extractable void formers improve the performance of voided slabs and minimize environmental impact [229,230].

The adoption of voided slab technology faces challenges related to structural performance, fire resistance, and market acceptance. Concerns about load-bearing capacity and deflection can be addressed through experimental studies, finite element analyses, and standardized design guidelines [213]. Fire safety risks, due to the presence of voids, require research into fire-resistant materials and thorough testing to ensure compliance with building codes. Additionally, market resistance stems from established construction practices and limited familiarity with this technology. Educational initiatives, case studies, and industry outreach can help promote awareness and facilitate wider adoption. By overcoming these challenges, voided slabs can become a key solution in sustainable construction [50,213].

4.5. Use of Recycled Aggregate or Waste

The incorporation of recycled aggregates and industrial by-products into concrete presents a viable strategy for reducing its carbon footprint and promoting sustainability. Recycled concrete aggregates (RCA), sourced from demolished structures, can effectively replace virgin aggregates, reducing the demand for quarrying and lowering transportation emissions. Studies have demonstrated that RCA can achieve mechanical properties comparable to those of natural aggregates, making it a feasible alternative without compromising structural integrity [231,232].

Industrial by-products, such as crushed glass, plastic waste, and rubber, further enhance the sustainability of concrete production. These materials reduce reliance on natural resources while contributing to improved durability and performance in concrete applications. Research highlights the potential of industrial by-products to minimize environmental impacts and enhance the mechanical properties of concrete [2,233].

The environmental benefits of using recycled materials in concrete extend beyond embodied carbon reduction. By substituting natural aggregates with recycled alternatives, the construction industry can significantly decrease landfill waste and mitigate the environmental impact of quarrying. Studies have shown that incorporating recycled materials reduces greenhouse gas

emissions associated with concrete production, thereby contributing to a more sustainable construction process [234,235].

Waste mineral powders, used as supplementary cementitious materials, offer another sustainable solution. These materials enhance the strength, durability, and impermeability of concrete while reducing its carbon footprint. Research indicates that incorporating waste mineral powders leads to improved mechanical performance, making it a practical option for sustainable construction [236].

Lifecycle assessments (LCA) of concrete containing recycled aggregates provide valuable insights into the environmental benefits of these materials. LCA quantifies reductions in embodied carbon and other environmental impacts, helping to establish the sustainability credentials of recycled materials in construction. Recent studies emphasize the importance of LCA in promoting environmentally conscious practices within the construction industry [237].

5. Analysis of the Embodied Carbon in Various Floors Systems

The comparison of embodied carbon based on floor types in concrete structures examines the environmental impact of various flooring designs, focusing on the greenhouse gas emissions associated with their lifecycle. As the construction industry increasingly prioritizes sustainability, understanding how different floor types contribute to embodied carbon is crucial for architects, builders, and policymakers. This topic is notable due to the significant role floors play in a building's overall carbon footprint, which can account for up to 50% of total emissions in capital projects.

In concrete structures, the floor plays a vital role in influencing total embodied carbon due to its material composition and design [239]. Studies have shown that different flooring systems contribute differently to the overall carbon footprint, with variations based on the type of concrete and insulation materials used [3].

The choice of floor type in concrete structures significantly impacts embodied carbon, material use, and energy efficiency. Flat floors require more concrete than pitched floors due to their larger surface area and structural support needs. Research shows that the embodied carbon of multi-story buildings varies considerably based on the floor system used [242]. Flooring material choices significantly affect a building's embodied carbon. Green floors with vegetation offer insulation benefits and reduce energy use, partially offsetting concrete's carbon impact. Traditional materials like metal or asphalt may have higher embodied carbon depending on their production and lifecycle. Life-cycle assessments (LCAs) help compare emissions from different floor types, enabling informed, sustainability-focused design decisions. The study emphasizes performance-based approaches for sustainable concrete floor design [243].

Several researchers have discussed the differences in the environmental and economic performance of available floor systems. Flat slabs are generally considered economical for spans up to 8 or 9 meters, while post-tensioned flat slabs are regarded as cost-effective for spans extending up to 12 or 13 meters. However, although span ranges are provided where various floor systems demonstrate economic efficiency, no specification is made regarding which system is the most economical for a given span within these ranges [21]. Embodied carbon of several slab types was compared for a range of spans, and it was observed that waffle slabs were optimum for all viable spans, with hollow-core slabs having the second-lowest embodied carbon for spans longer than 7 meters. It was further noted that flat slabs, two-way slabs, and post-tensioned flat slabs exhibited similar embodied carbon values for spans between 4 and 7 meters [244]. Several floor solutions, including flat slabs, post-tensioned flat slabs, and composite slabs, were compared across three different scenarios, and it was concluded that no structural scheme consistently resulted in the lowest embodied carbon [245]. One-way spanning slabs, flat slabs with and without drop panels, were compared for active and passive reinforcement within a fixed column grid. It was found that all three slab types achieved up to a 49% reduction in embodied energy with post-tensioning. Additionally, the reinforced flat slab was observed to have 7% less embodied energy compared to the other two reinforced solutions, which exhibited nearly identical embodied energy values [246]. A case study

demonstrated that voided slabs could achieve a reduction in embodied carbon compared to an equivalent solid concrete floor solution [247]. However, an analysis of several floor options highlighted that the lightweight materials used in voided slabs can increase the total embodied energy compared to flat slabs [248].

Innovative floor systems utilizing membrane action instead of traditional bending improve load distribution and reduce material usage. This approach enables thinner slabs, leading to significant material savings while maintaining structural integrity. Research shows that membrane action enhances load capacity, offering greater design flexibility and more efficient material use [220].

This design approach has been shown to reduce concrete volume by 20-40%, resulting in substantial reductions in embodied carbon. The use of thinner slabs also reduces the overall weight of structures, leading to cost savings in foundations and other structural elements. Studies highlight the material and cost efficiencies achieved through slab optimization for membrane action [249].

Membrane action in innovative floor systems enhances material efficiency and structural performance, enabling longer spans and greater design flexibility. This approach is particularly beneficial for parking garages, open spaces, and seismic regions, as it improves load distribution, seismic resistance, and earthquake damage mitigation. By optimizing structural and seismic performance, these designs offer both sustainability and resilience, expanding possibilities for modern construction [207].

From a sustainability perspective, innovative floor systems contribute to reducing embodied carbon by optimizing material use. Furthermore, these systems promote lower energy consumption during building operations and improve occupant comfort. Research underscores their role in enhancing both environmental and operational sustainability, achieving substantial reductions in embodied and operational energy use [211].

Incorporating innovative floor systems into the design of reinforced concrete structures aligns with broader efforts to reduce embodied carbon and promote sustainability. By combining alternative materials, structural optimization, effective deflection management, voided floor systems, and recycled aggregates, the construction industry can significantly mitigate its environmental impact while enhancing the performance and longevity of concrete structures.

Flat slabs are a simple and efficient floor design, consisting of a continuous slab supported directly by columns or walls without the use of beams. Beam and slab systems, on the other hand, incorporate a series of beams supporting a slab, which can provide greater span capabilities and design flexibility [252,253]. Ribbed slabs feature a series of parallel ribs or joists, often with a thin top slab, which can reduce the overall concrete volume and, consequently, the embodied carbon [254].

Waffle slabs are a type of two-way ribbed slab system, where the ribs are arranged in a grid pattern, creating a "waffle" appearance. Hollow-core slabs are a precast concrete system with pre-formed voids or cavities within the slab, reducing the overall concrete volume. Nervi-style slabs are a unique design that utilizes a series of intersecting curved shells or thin slab elements to create an efficient and structurally expressive floor system. Arched slabs, on the other hand, feature a curved, vaulted design that can offer both architectural and structural benefits. To understand the embodied carbon implications of these various floor systems, it is essential to analyze the materials and construction methods involved [252,253].

Flat slabs generally require a significant amount of concrete and reinforcement, as the entire slab must be designed to span between supports. In contrast, beam and slab systems can distribute the loads more efficiently, potentially reducing the overall concrete volume [255]. Ribbed slabs, waffle slabs, and hollow-core slabs all have the potential to reduce the embodied carbon of the floor structure by minimizing the concrete required, either with ribs, voids, or precast elements [256,257].

5.1. Flat Slab

Flat slabs are a reinforced concrete floor system consisting of a flat, continuous slab supported directly by columns without the use of beams [242,257,258]. Commonly used in multi-story buildings, flat slabs are valued for their simplicity and reduced formwork requirements. Optimization focuses

on minimizing slab thickness and reinforcement density, which can reduce material usage and embodied carbon. Advanced BIM tools facilitate these optimizations [257]. Replacing cement with supplementary materials like fly ash or GGBS can further lower the embodied carbon footprint by up to 25% [145].

The embodied carbon values associated with flat slabs can vary significantly based on factors such as thickness, span length, and the type of concrete used. Studies indicate that optimizing the thickness and reinforcement ratios can lead to a reduction in embodied carbon by up to 20% [145].

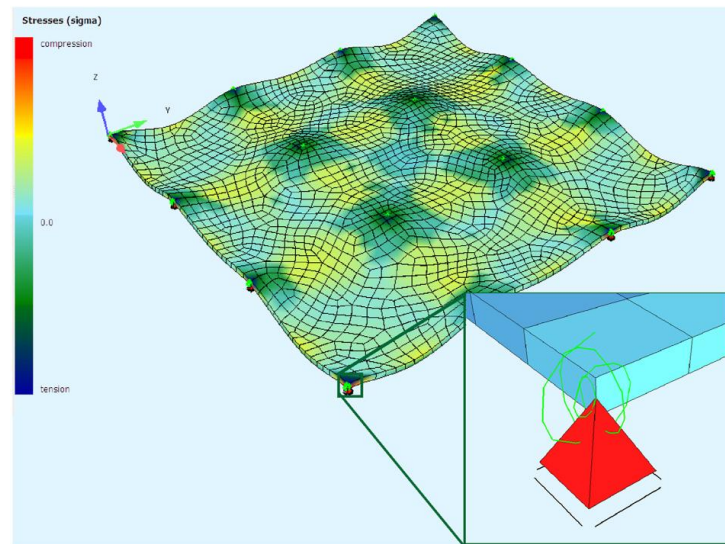


Figure 5. Finite element model of flat slab for estimating non-linear long-term deflection [142].

For instance, a 200 mm thick flat slab with an 8-meter span using standard concrete (C25/30) yielded 250 kg CO₂/m² [142]. In another study, a 250 mm thick flat slab over a 10-meter span with high-strength concrete (C40/50) resulted in 350 kg CO₂/m² [242]. An optimized mix with supplementary cementitious materials (SCMs) for a 200 mm thick slab over 8 meters reduced the embodied carbon to 180 kg CO₂/m² [259]. Lightweight concrete (C20/25) was used in a 200 mm thick flat slab with a 6-meter span, achieving 220 kg CO₂/m² [260]. Lastly, a 300 mm thick flat slab over a 15-meter span using standard concrete (C30/37) resulted in 450 kg CO₂/m² [261].

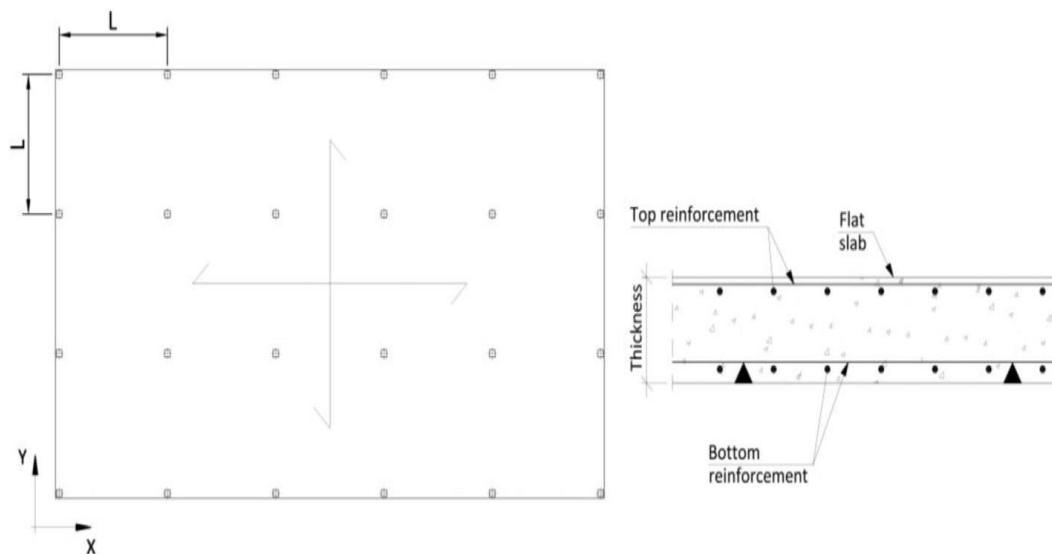


Figure 6. Details of Flat Slab [71].

5.2. Beam and Slab

Beam and slab system is a reinforced concrete floor system that consists of a slab supported by a network of beams, which in turn are supported by columns [184,242,258]. The beams and slabs work together to carry the loads. This system is widely used in multi-story buildings and is known for its flexibility in accommodating various architectural layouts [242,258]. Optimization involves adjusting beam spacing and dimensions to reduce material use, achieving up to a 15% reduction in embodied carbon [151].

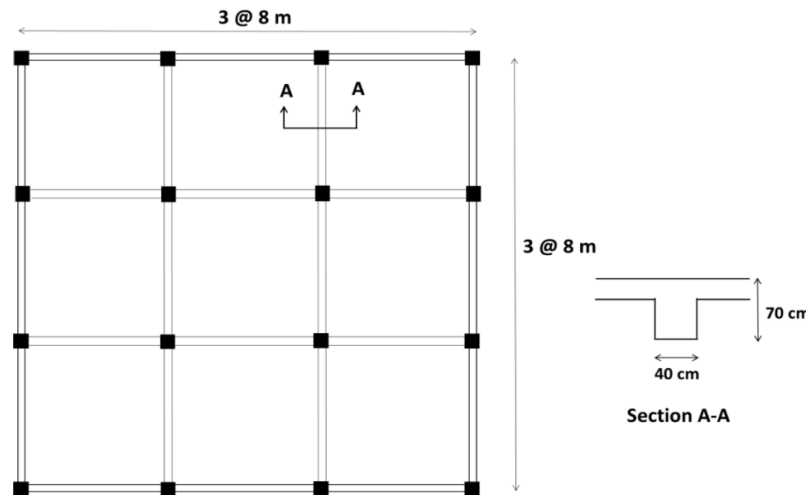


Figure 7. Representative building frame layout [250].

The beam and slab system typically has a higher embodied carbon due to the additional materials required for beams, with values ranging from 180 to 500 kg CO₂/m². For example, a 250 mm thick slab with 6-meter spans using standard concrete (C25/30) yielded 320 kg CO₂/m² [262]. Additionally, a 300 mm thick slab over a 10-meter span with high-strength concrete (C40/50) resulted in 450 kg CO₂/m² [263]. Lastly, 300 mm thick slab over a 15-meter span with standard concrete (C30/37) yielded 500 kg CO₂/m² [264].

5.3. Ribbed

Ribbed slab is a reinforced concrete floor system that consists of a thin slab with regularly spaced ribs or beams running in one or two directions [242]. The ribs help reduce the overall concrete volume compared to a flat slab, leading to potential savings in material and embodied carbon [265]. Optimization focuses on spacing and rib depth to balance load distribution and material usage. Incorporating recycled aggregate concrete can reduce the embodied carbon footprint by 10–15% [265].

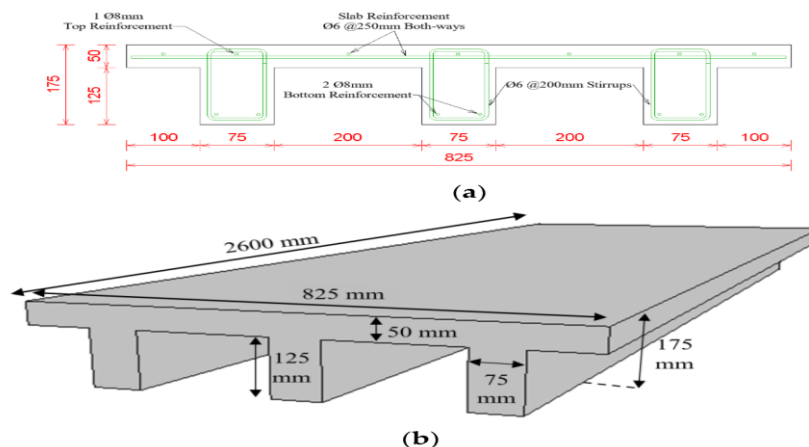


Figure 8. Details of Ribbed slab (dimensions are in mm): (a) Concrete dimensions and steel reinforcement in ribs and top slab; (b) isometric view showing concrete dimensions; [269].

Ribbed slabs are designed to reduce material usage while maintaining structural integrity, with embodied carbon values ranging from 230 to 400 kg CO₂/m². For instance, a 300 mm deep ribbed slab with an 8-meter span using standard concrete (C25/30) yielded 280 kg CO₂/m² [266]. A 300 mm deep ribbed slab spanning 12 meters with conventional concrete (C30/37) resulted in 370 kg CO₂/m² [267]. Finally, a 300 mm deep ribbed slab with a 9-meter span using recycled aggregates (C30/37) achieved 280 kg CO₂/m² [268].

5.4. Waffle

Waffle slabs are known for their efficiency in material use, leading to lower embodied carbon values ranging from 180 to 350 kg CO₂/m². For example, a 300 mm waffle slab with spans of 9 meters using standard concrete (C25/30) yielded 220 kg CO₂/m² [270]. Additionally, a 400 mm waffle slab over a 12-meter span with high-strength concrete (C40/50) resulted in 340 kg CO₂/m² [271]. For instance, a 250 mm waffle slab with an 8-meter span using recycled aggregates (C30/37) showed 210 kg CO₂/m² [272]. In another study, a 300 mm waffle slab spanning 10 meters with lightweight concrete (C20/25) achieved 300 kg CO₂/m² [274]. A 200 mm waffle slab with a 6-meter span using standard concrete (C25/30) yielded 175 kg CO₂/m² [275]. Lastly, a 400 mm waffle slab over a 15-meter span with high-performance concrete (C50/60) resulted in 350 kg CO₂/m² [275].

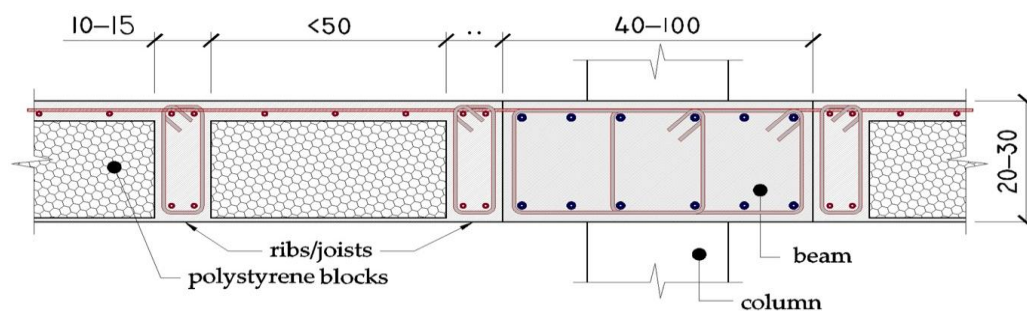


Figure 9. Typical detail of a wide beam and joisted slab used in Albania; [291].

5.5. Post-Tensioned Concrete Floor

Post-tensioned slabs are designed to use less concrete and steel by pre-stressing the reinforcement. A reinforced concrete floor system that utilizes high-strength steel tendons or cables that are tensioned after the concrete has hardened. The post-tensioning process introduces compressive forces into concrete, which improves its resistance to tensile stress and can result in thinner, more efficient floor structures [276]. This system is commonly used in large-span buildings, such as stadiums and bridges, where reduced self-weight is critical [277]. Post-tensioning can decrease material usage by 20–30%, significantly reducing embodied carbon [259–278].

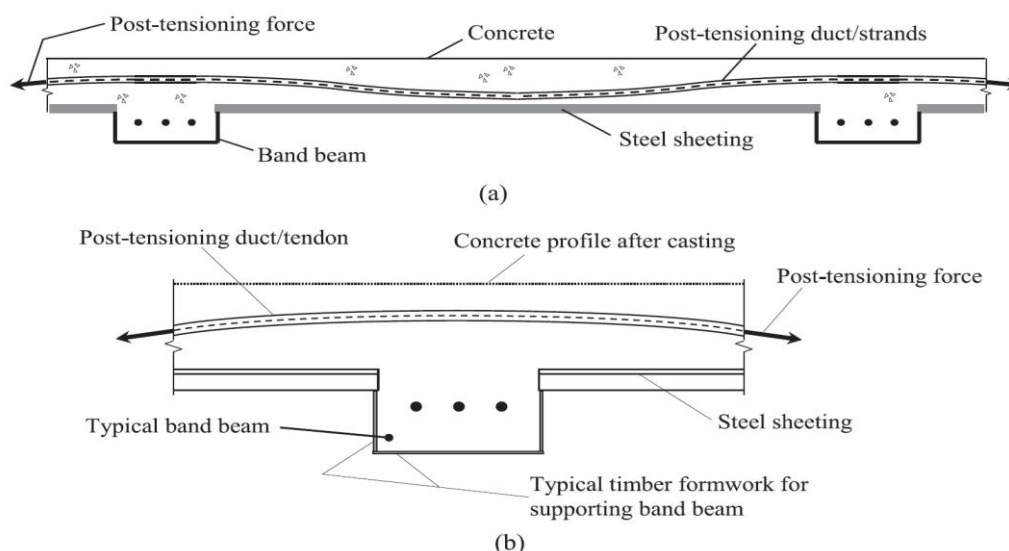


Figure 10. (a) Typical elevation of a post-tensioned composite slab supported by band beams; (b) Typical construction detail of profiled steel sheeting being supported from formwork of band beam before concrete pour; [292].

Post-tensioned concrete floors utilize high-strength steel tendons to enhance structural performance and reduce material usage. The embodied carbon for spans of 8 to 16 meters, with slab thickness between 150 mm and 250 mm, depending on the span and use concrete grades of C40/50 [259] is approximately from 180 to 300 kg CO₂/m².

For instance, a 200 mm thick post-tensioned slab with an 8-meter span using standard concrete (C30/37) yielded 190 kg CO₂/m² [279]. Similarly, a 200 mm thick slab over a 10-meter span with high-strength concrete (C40/50) resulted in 240 kg CO₂/m² [280]. In another example, a 300 mm thick post-tensioned slab with a 12-meter span using recycled aggregates (C30/37) achieved 290 kg CO₂/m² [281]. Finally, a 300 mm thick slab spanning 15 meters with lightweight concrete (C40/50) showed 300 kg CO₂/m² [282].

5.6. Hollowcore

Hollowcore slab is a precast, prestressed concrete floor system that consists of a series of parallel, hollow cores running the length of the slab [242,265]. Hollow cores reduce the overall concrete volume, making hollowcore slabs a more sustainable option compared to solid slabs [242].

The embodied carbon for hollow-core slabs ranges from 180 to 320 kg CO₂/m². A 300 mm thick hollow-core slab with a 10-meter span using high-strength concrete (C40/50) and a thinner slab with higher-strength concrete (C50/60) both resulted in an embodied carbon of 300 kg CO₂/m² [263,283]. Additionally, a 300 mm thick hollow-core slab with a 12-meter span using standard concrete (C30/37) yielded 320 kg CO₂/m² [284]. A 200 mm thick hollow-core slab with a 5-meter span using low-carbon concrete (C25/30) yielded 170 kg CO₂/m² [285].

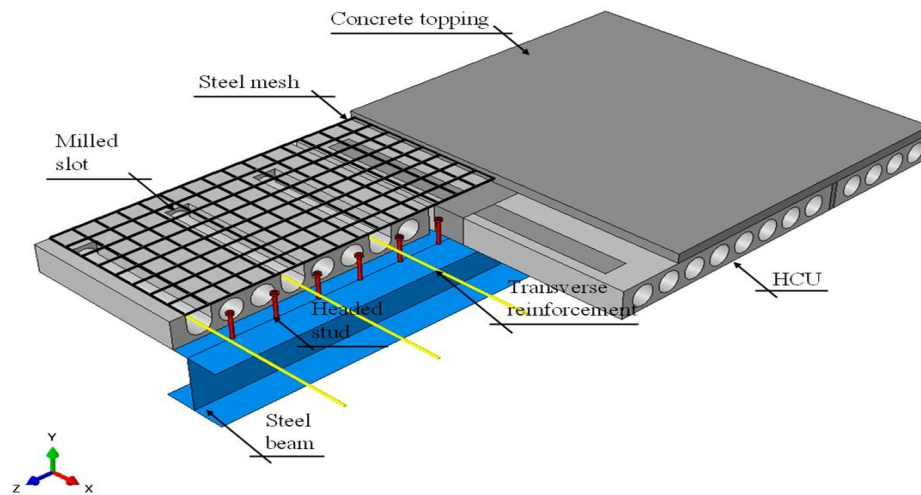


Figure 11. Parts of Steel-Concrete composite beams with a hollow core slab, 150 mm of hollowcore slab depth and 55 mm of concrete topping with a squared end; [293].

5.7. Nervi-style Slab

Nervi-style slab is a thin-shell concrete floor system, characterized by its curved, hyperbolic paraboloid shape [108]. The thin, curved design can potentially reduce the concrete volume compared to a flat slab, leading to lower embodied carbon. For example, a 250 mm thick Nervi-style slab with a 9-meter span using standard concrete (C25/30) yielded 240 kg CO₂/m² [286]. Additionally, a 200 mm thick slab with an 8-meter span using recycled aggregates (C30/37) showed 230 kg CO₂/m² [287].

5.8. Arched Slab

Arched slab is a reinforced concrete floor system that features a curved, arched geometry [108], to distribute loads effectively, which can lead to a reduction in material usage [151]. Like the Nervi-style slab, the curved design can potentially reduce the concrete volume compared to a flat slab, which may result in lower embodied carbon [108]. The embodied carbon values ranging from 200 to 380 kg CO₂/m². For instance, a 200 mm thick arched slab with a 6-meter span using standard concrete (C25/30) yielded 200 kg CO₂/m² [288]. In another study, a 300 mm thick slab with a 9-meter span using standard concrete (C40/50) yielded 260 kg CO₂/m² [289]. Furthermore, a 300 mm thick slab with a 10-meter span using recycled aggregates (C30/37) yielded 310 kg CO₂/m² [290].

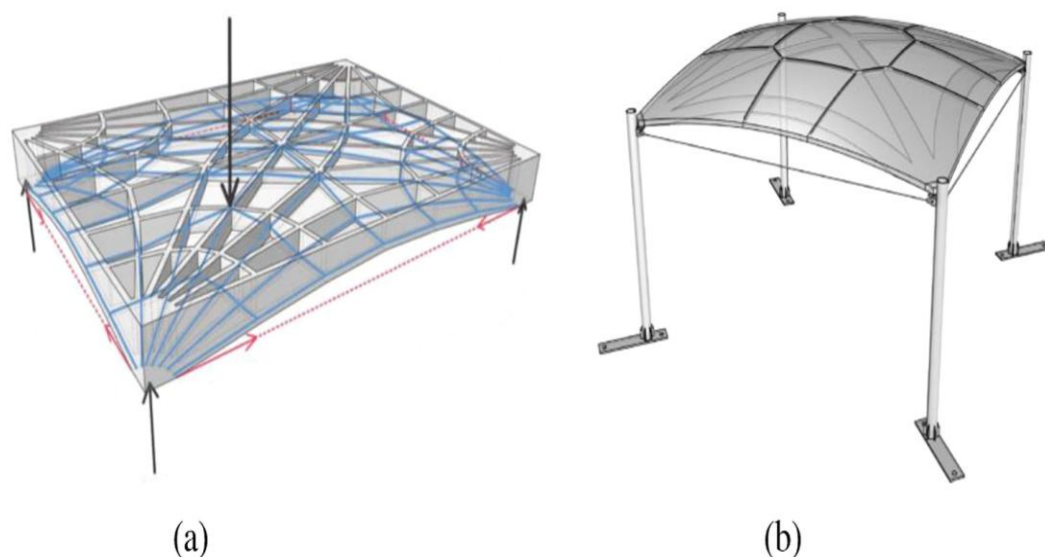


Figure 12. (a) Funicular (arched) floors with external arch ties between columns investigated and (b) arched thin concrete shell floor plate investigated in [147].

6. Discussion

The comprehensive analysis of eight different floor systems revealed significant variations in embodied carbon performance. Post-Tensioned Concrete Slab systems demonstrated superior environmental performance with the lowest mean embodied carbon ($247 \pm 32 \text{ kgCO}_2\text{e/m}^2$), followed by Hollow-Core Slab systems ($250 \pm 47 \text{ kgCO}_2\text{e/m}^2$). In contrast, Beam and Slab systems consistently showed the highest environmental impact ($388 \pm 77 \text{ kgCO}_2\text{e/m}^2$). The hierarchical arrangement of systems based on mean embodied carbon values is as follows:

- 1. Post-Tensioned Concrete Floor ($247 \pm 32 \text{ kgCO}_2\text{e/m}^2$)
- 2. Hollow-Core Slab ($250 \pm 47 \text{ kgCO}_2\text{e/m}^2$)
- 3. Waffle Slab ($263 \pm 61 \text{ kgCO}_2\text{e/m}^2$)
- 4. Arched Slab ($270 \pm 58 \text{ kgCO}_2\text{e/m}^2$)
- 5. Nervi-style Slab ($274 \pm 47 \text{ kgCO}_2\text{e/m}^2$)
- 6. Flat Slab ($286 \pm 84 \text{ kgCO}_2\text{e/m}^2$)
- 7. Ribbed Slab ($308 \pm 59 \text{ kgCO}_2\text{e/m}^2$)
- 8. Beam and Slab ($338 \pm 77 \text{ kgCO}_2\text{e/m}^2$)

6.1. Span-Based Performance Analysis

The investigation of embodied carbon performance across different span ranges revealed distinct patterns and significant variations in system efficiency. The analysis was conducted across three primary span categories: short spans (0-6m), medium spans (6-10m), and long spans (10-15m), with each category demonstrating unique characteristics and performance metrics.

6.1.1. Short-Span Systems (0-6m)

Analysis of short-span applications revealed that Waffle Slab systems demonstrated superior environmental performance, with the lowest embodied carbon values ($172 \pm 8 \text{ kgCO}_2\text{e/m}^2$). This exceptional performance can be attributed to efficient material distribution and the ability to utilize lower-strength concrete (typically C25/30). Flat Slab systems followed closely ($185 \pm 13 \text{ kgCO}_2\text{e/m}^2$), offering a good balance between simplicity and environmental impact.

In this span range, most systems maintained relatively thin profiles (200-250mm), with Flat Slabs occasionally requiring increased depth (up to 300mm) for specific loading conditions.

Notably, traditional Beam and Slab systems demonstrated the highest embodied carbon values ($296 \pm 19 \text{ kgCO}_2\text{e/m}^2$) even in short spans, suggesting inefficient material utilization for these modest span requirements.

Table 4. Amount of Embodied Carbon for Short-Span.

Floor Type	Embodied Carbon ($\text{kgCO}_2\text{e/m}^2$)	σ	Concrete Grade	Thickness (mm)
Waffle Slab	172	± 8	C25/30	200-250
Flat Slab	185	± 13	C25/30	200-300
Hollow-Core Slab	193	± 15	C30/37	200-250
Arched Slab	195	± 10	C25/30	200-250
Post-Tensioned Concrete Floor	220	± 17	C40/50	200-250
Nervi-style Slab	223	± 10	C30/37	200-250
Ribbed Slab	253	± 39	C30/37	200-250
Beam and Slab	296	± 19	C35/45	200-250

6.1.2. Medium-Span Systems (6-10m)

The medium-span category revealed more pronounced differentiation between systems. Post-Tensioned Concrete Floor systems emerged as the most efficient solution (245 ±28 kgCO₂e/m²), closely followed by Hollow-Core Slabs (247 ±37 kgCO₂e/m²). This performance advantage can be attributed to their optimized use of high-strength materials and efficient structural forms.

A notable trend in this span range was the increased variation in performance within each system type, as evidenced by larger standard deviations. Flat Slab systems, in particular, showed high variability, indicating sensitivity to specific design parameters and loading conditions. The required thickness range expanded significantly (200-400mm), reflecting the increased structural demands of longer spans.

The performance gap between specialized and traditional systems became more pronounced, with Beam and Slab systems showing significantly higher embodied carbon values (407 ±67 kgCO₂e/m²).

Table 5. Amount of Embodied Carbon for Medium-Span.

Floor Type	Embodied Carbon (kgCO ₂ e/m ²)	σ	Concrete Grade	Thickness (mm)
Post-Tensioned Concrete Floor	245	±28	C40/50	200-300
Hollow-Core Slab	247	±37	C35/45	200-300
Waffle Slab	264	±51	C35/45	200-400
Nervi-style Slab	271	±32	C35/45	200-250
Arched Slab	281	±37	C30/37	200-250
Flat Slab	282	±71	C30/37	200-250
Ribbed Slab	293	±43	C35/45	200-250
Beam and Slab	407	±67	C40/50	200-250

6.1.3. Long-Span Systems (10-15m)

Long-span applications demonstrated the most significant variations in performance and the highest absolute embodied carbon values. Post-Tensioned Concrete Floor systems maintained their environmental advantage (262 ±39 kgCO₂e/m²), showing remarkable efficiency even at extended spans. This performance is particularly noteworthy given the structural challenges associated with longer spans.

The data revealed a clear trend toward increased material requirements across all systems, with thickness ranges typically starting at 250mm and extending to 400mm in some cases. Despite this general trend, Post-Tensioned systems maintained relatively modest thickness increases, demonstrating superior structural efficiency.

Table 6. Amount of Embodied Carbon for Long-Span.

Floor Type	Embodied Carbon (kgCO ₂ e/m ²)	σ	Concrete Grade	Thickness (mm)
Post-Tensioned Concrete Floor	262	±39	C40/50	250-300
Hollow-Core Slab	304	±18	C40/50	250-300
Waffle Slab	307	±49	C40/50	200-400
Nervi-style Slab	313	±51	C40/50	200-00
Arched Slab	335	±32	C35/45	250-400
Ribbed Slab	384	±17	C40/50	250-300
Flat Slab	388	±50	C35/45	250-300
Beam and Slab	442	±57	C45/55	250-300

6.2. Mechanisms of Carbon Reduction

The variation in embodied carbon performance can be attributed to specific characteristics of each system:

1. Post-Tensioned Concrete Floor:
 - Achieves efficiency through active force distribution via tensioned cables
 - Reduces concrete volume through controlled deflection
 - Enables thinner sections due to pre-compression
 - Minimizes reinforcement through prestressing forces
2. Hollow-Core Slab
 - Removes non-structural concrete through void formation
 - Optimizes material placement through standardized production
 - Reduces self-weight while maintaining depth for structural efficiency
 - Benefits from factory-controlled production quality
3. Waffle Slab
 - Creates efficient two-way spanning action.
 - Removes concrete from low-stress zones.
 - Maintains structural depth with minimal material.
 - Provides inherent ceiling aesthetics reducing finishing materials.
4. Arched Slab
 - Utilizes natural compressive force paths.
 - Minimizes tensile stresses through geometric optimization.
 - Reduces material in non-critical areas.
 - Benefits from structural form efficiency.
5. Nervi-style Slab
 - Optimizes material placement along force paths.
 - Creates efficient ribbed patterns following stress lines.
 - Combines aesthetic and structural efficiency.
 - Reduces material through biomimetic design principles.
6. Flat Slab
 - Simplifies formwork reducing material waste.
 - Provides direct force transfer to columns.
 - Eliminates beam material volume.
 - Allows for reduced floor-to-floor height.
7. Ribbed Slab
 - Concentrates material in primary stress zones.
 - Provides efficient one-way spanning action.
 - Reduces self-weight through regular void patterns.
 - Maintains structural depth with less material.
8. Beam and Slab
 - Traditional force distribution through distinct elements.
 - Higher material use due to separate structural components.
 - Provides clear load paths.
 - Requires additional depth for beam elements.

7. Conclusions

The analysis of eight floor systems across varying spans yields several significant conclusions:

The choice of floor system has a substantial impact on embodied carbon, with variations of up to 40% between the best and worst-performing systems. Post-Tensioned Concrete Floor systems

consistently demonstrate superior environmental performance across all span ranges, particularly in medium to long spans where their efficiency becomes most apparent.

Span length emerges as a critical factor in environmental impact, with all systems showing increased embodied carbon as spans increase. However, the rate of increase varies significantly between systems, suggesting that careful system selection becomes increasingly important for longer spans. System efficiency exhibits distinct patterns across span ranges:

- For short spans (0-6m), Waffle Slabs offer the best environmental performance
- In medium spans (6-10m), Post-Tensioned and Hollow-Core systems demonstrate optimal efficiency
- For long spans (10-15m), Post-Tensioned systems maintain their advantage, though with higher absolute carbon values

These findings suggest that optimizing floor system selection based on span requirements can significantly reduce embodied carbon in construction. The results also indicate that traditional Beam and Slab systems, despite their widespread use, may need reconsideration from an environmental perspective, particularly when alternative systems are viable.

Future research should focus on investigating the relationship between initial cost and embodied carbon to provide a more comprehensive decision-making framework for practitioners. Additionally, consideration of maintenance requirements and end-of-life scenarios could further inform the long-term environmental impact of these systems.

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