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Review

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

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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

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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 (CO_2) 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 GBP 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 is the second most used material globally after water, with an annual per capita consumption of about 1 cubic meter [1]. Over 30 billion tons of reinforced concrete is produced worldwide each year, with cementitious materials contributing 6–8% of global anthropogenic emissions [2]. By 2020, the global production of concrete and cement exceeded 14.0 billion m^3 and 4.2 billion tons, respectively [3]. Notably, around 60% of ready-mixed concrete in Europe is consumed by building construction [4], illustrating the sector's significance in meeting decarbonization targets set in policies like the European Green Deal [5]. Concrete underpins infrastructure projects ranging from bridges and buildings to air and maritime terminals [6]. Its widespread use stems from performance benefits, the local availability of raw materials [7] and its economic importance in creating jobs and contributing to the GDP [8].

However, concrete production alone accounts for approximately 50% of global primary energy and resource demand [9], 30% of total waste generation [10], 15% of freshwater consumption [11] and 33% of anthropogenic greenhouse gas emissions [12]. Various floor systems exist, each with distinct advantages in construction speed, cost and sustainability [13–17]. Despite innovations in design, global carbon dioxide emissions surpassed 34 gigatons in 2020 (around 4.48 metric tons per person), and CO_2 concentrations exceeded 417 parts per million [18,19]. Rising average global temperatures have accelerated glacier loss, impacted biodiversity and intensified heat waves, prompting international agreements such as the 2015 Paris Agreement, which aims to keep temperature increases below 2 °C—ideally below 1.5 °C—relative to pre-industrial levels [20,21]. The United Kingdom has pledged to achieve net-zero emissions by 2050 [22]. Six greenhouse gases contribute up to 97% of global warming effects, with CO_2 responsible for around 77% of these emissions [23–25]. Embodied carbon—representing the greenhouse gas emissions across a structure's entire life cycle—forms a large portion of total global emissions, at around 11% [26,27]. Life cycle assessments (LCAs) measure these emissions in CO_2 equivalent (CO2e) units [28]. Cement production alone accounts for approximately 8% of global emissions, releasing 0.8–0.9 kg CO_2 for each kilogram of clinker [2,28], while steel reinforcement contributes an additional 6–7% [29]. Combined, concrete and steel often comprise 65–75% of a building's embodied carbon [30], with floor systems alone potentially representing up to 75% of superstructure emissions [31]. As operational energy use declines with improved building efficiency, the proportion of embodied carbon in overall emissions is expected to grow [32,33]. Researchers thus underscore the urgent need to reduce embodied carbon emissions within the construction sector [34,35], a sector that remains under increasing scrutiny due to its substantial impact on climate change [36].

Concrete structural elements must satisfy criteria for resistance, serviceability and durability [37]. Yet, multiple design solutions can fulfill these requirements while exhibiting different embodied carbon intensities. Various strategies have been proposed to minimize embodied carbon in concrete floors, including parametric design optimization [38,39], comparative analyses of alternative systems [40] and shape optimization [41]. Industry guidelines provide span-to-depth ratios as a starting point for beam and slab design [13–15,42], but applying iterative approaches to sectional dimensions and reinforcement configurations can unveil solutions that yield lower embodied carbon [42,43]. Shape optimization methods using flexible formwork have demonstrated material savings of up to 44% in beams or slabs [44,45], and ongoing research highlights how refining geometry, reinforcement and depth profiles can further lower environmental impacts [46].

Parametric studies of flat slab systems also show that factors like slab thickness, concrete grade, column spacing and reinforcement configuration significantly influence a design's carbon footprint [47]. Modern optimization approaches integrate deflection controls (using the equivalent frame method [48], finite element modeling [49] or non-linear long-term deflection estimates [50]) to ensure that performance remains acceptable as designers push beyond conventional limits for span-to-depth ratios. Studies have shown it is possible to reduce embodied carbon in floor systems without drastically altering standard construction practices [17,40,51], while more radical approaches—such as novel low-carbon slabs relying on compressive membrane action—require early-stage design changes [52].

Beyond environmental considerations, the construction industry significantly impacts the global economy, valued at about USD 10 trillion per year (13% of the world economy) [23]. Projections estimate this value to grow to USD 17.5 trillion by 2030, at a rate of nearly 4% per year [53]. Hence, strategies targeting both cost and embodied carbon through multi-objective optimization are increasingly critical. The adoption of new design tools, construction techniques and procurement strategies can allow the built environment to evolve sustainably while continuing to support economic development.

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 with floor systems being 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 [54]. 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 [55,56]. BS EN 15978 [57] and BS EN ISO 14044 [58] have standardized 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 Life Cycle): Potential benefits from material reuse or recycling.

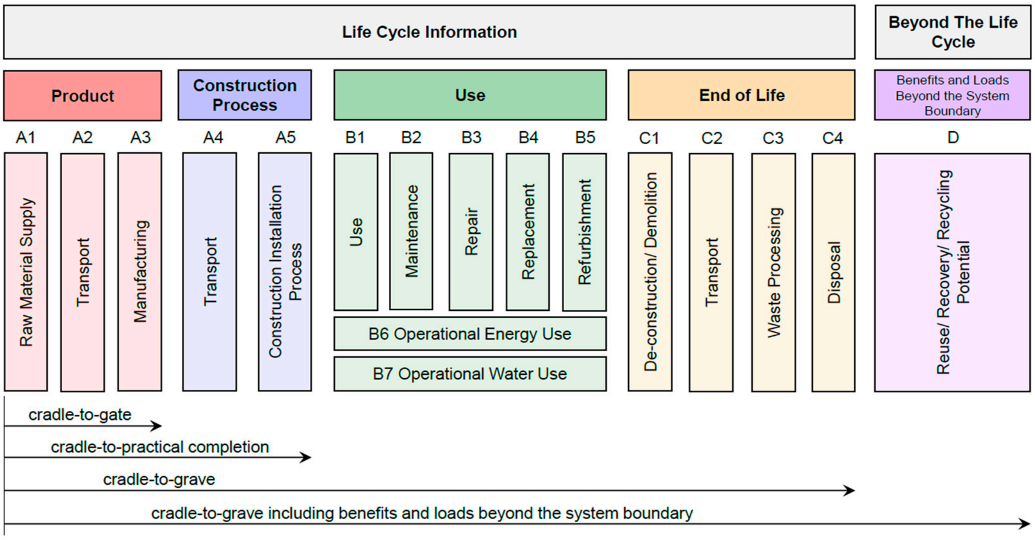


Figure 1. Life cycle information for buildings according to BS EN 15978 [57].

Due to the significance of the present climate emergency, CO_2 equivalent emissions and consumption of energy have been widely used as indicators for the environmental impact assessment of buildings [24,59,60]. The Inventory of Carbon and Energy by Circular Ecology suggests that CO_2 equivalent emissions can be considered a more representative measurement of the environmental impact [61].

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 [57]. Studies suggest that 50–75% of the embodied carbon in a building can be attributed to this stage [59]. As a result, reducing the embodied carbon in concrete structures requires significant intervention during the early design and material selection phases [62].

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 [63,64]. 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 [65].

3.1.2. Inventory Analysis (LCI)

In this phase, data are 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 [24,66].

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 [67].

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 encompasses all greenhouse gas (GHG) emissions throughout a material's life cycle, from raw material extraction and manufacturing to transportation, installation, maintenance and end-of-life disposal. In highly energy-efficient buildings with minimal operational energy demands, embodied carbon can constitute as much as 80% of total life cycle emissions [63,64].

Its assessment typically relies on life cycle assessment (LCA) tools and databases, which provide emission factors reflecting the life cycle impacts of various materials. Consequently, energy-intensive products like concrete and steel exhibit higher embodied carbon than sustainably sourced timber [65,66]. Moreover, factors such as transportation distances, construction methods and the potential for recycling or reuse play significant roles in determining a material's overall carbon footprint. By integrating embodied carbon analysis early in the design and decision-making processes, architects and builders can make choices that substantially reduce a project's environmental impact [24,67].

3.3. Embodied Carbon Calculations

The embodied carbon factor quantifies the GHG emissions (in kgCO2e/kg) associated with a specific material or product, serving as a fundamental metric to calculate total embodied carbon in buildings or infrastructure (Table 1; [63,64]). Because the production methods, energy sources and transportation vary, the embodied carbon factors range widely; for instance, concrete may fall between 100 and 300 kgCO2e/kg, while steel can exceed 1000 kgCO2e/kg [65,66]. In contrast, sustainably sourced timber can be as low as 50 kgCO2e/kg [24].

Material choices heavily influence overall embodied emissions, given that steel, concrete and aluminum production typically relies on energy-intensive, fossil-fuel-based processes. Design decisions regarding building systems and material optimization further affect total emissions [36,68]. Moreover, adopting alternative binders in concrete or low-carbon steel production can reduce the embodied carbon factor [67].

Embodied carbon is calculated via life cycle assessment (LCA) methods, using environmental product declarations (EPDs) and emission factors. The generalized formula for embodied carbon at each life cycle stage is provided in [62].

$$EC_{total} = \sum (Material\ Mass \times Carbon\ Factor_{Module}) \tag{1}$$

Calculating the embodied carbon in concrete structures spans the entire life cycle, from raw material extraction through end-of-life disposal. The process begins by quantifying all constituents—cement, aggregates, water and SCMs (e.g., fly ash, slag)—each with a carbon footprint in kgCO2e per unit [69]. Next, databases and tools provide embodied carbon coefficients for these components [70]. Reducing cement content, substituting alternative binders or incorporating recycled aggregates can significantly decrease the overall carbon footprint of reinforced concrete [71].

Table 1. Comparison of typical embodied energy and carbon values for a variety of engineering materials [61,72,73].

Materials	Embodied Carbon [kgCO2e/kg]	Materials	Embodied Carbon [kgCO2e/kg]
Concrete constituents		**Concrete example mixes (CEM I)**	
Portland cement *	0.912	C20/25 *	0.121
Fly ash *	0.008	C32/40 *	0.149
GGBS *	0.083	C40/50 *	0.172
Aggregate *	0.00747	**Metals**	
Water *	0.0008	Steel reinforcement *	1.99
Superplasticiser ‡	1.88	Hot-rolled steel section *	1.55
		Galvanised steel sheet *	2.76
Fibre materials		Aluminum extrusions *	6.83
Carbon fibre †	20.3	**Fibre composite matrix materials**	
Aramid fibre †	17.3	Epoxy †	6.60
Glass fibre †	3.00	Vinyl ester †	4.31
Basalt fibre †	0.057	Polyester †	2.54

* Source: Jones and Hammond (2019) [61]. † Source: Granta Design Ltd. (2018) [72]. ‡ Source: EFCA (2015) [73].

Life cycle assessment (LCA) offers a holistic approach to evaluating environmental impacts at every stage of a concrete structure's life, spanning production, transport, construction, maintenance and end-of-life processes [74]. Notably, carbonation, where concrete absorbs CO_2 over its service life, can offset around 11% of total emissions for ordinary Portland cement concrete [75]. Structural design also plays a pivotal role in reducing embodied carbon: strategies like optimizing mix designs, lowering cement content and employing low-carbon alternatives can substantially decrease emissions [76]. For instance, adopting thin-shell structures has been proposed to minimize the carbon footprint of concrete buildings without compromising structural integrity [77].

3.4. Uncertainty in Estimation of Embodied Carbon

The life cycle assessment (LCA) of buildings can employ various methods—statistical, process-based, economic input–output or hybrid—each with its own uncertainties [24,78]. Process-based LCA provides more detailed, reliable results but can be time-intensive and expensive, whereas input–output analyses are less precise for specific design variations [79]. Numerous databases supply embodied carbon values for common construction materials, derived from the literature, manufacturer data, environmental product declarations and both process-based and input–output analyses [80]. Organizations like RICS [81], UK Green Building Council [82] and IStructE [62] also offer guidelines and benchmarks.

Because embodied carbon is influenced by materials, products, systems and technologies [80,83], the coefficients used can vary widely due to geographic location, manufacturing technology, data sources and temporal factors [59,79,84,85]. As a result, any optimization study for concrete floors should acknowledge potential uncertainties in these coefficients [10,80]. For instance, the ratio of embodied carbon for concrete to steel can differ significantly—from 0.0208 to 0.4545—altering an optimal design outcome [86]. In extreme cases, estimates may fluctuate between 50% and 140% of baseline values under Monte Carlo simulations [87]. Figure 2 (in [87]) shows a breakdown by material type in a sample building. The Inventory of Carbon and Energy [61] indicates average embodied carbon for C28/35 concrete at 0.126 kgCO2e/kg, potentially rising to 0.136 with 100% CEM I or dropping to 0.099 with 40% fly ash substitution. Steel rebar averages 1.99 kgCO2e/kg globally, which can be reduced to 1.20 kgCO2e/kg using 85% recycled steel [61].

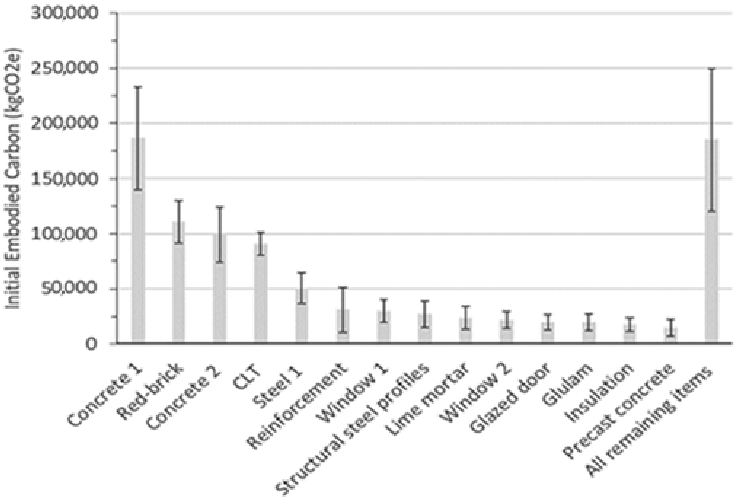


Figure 2. Uncertainty of embodied carbon by construction product [87].

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 [88]. The methods to minimize embodied carbon were 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 [10]. Effective approaches have been proposed, 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 [89].

The methods of minimizing embodied carbon in buildings were extensively reviewed in Annex 57 Subtask 4 by the Energy in Buildings and Communities Programme of the International Energy Agency (IEA EBC) [90]. The annex divided low-carbon strategies into three categories: (1) reduction in the amount of materials needed throughout the entire life cycle, (2) substitution of traditional materials for alternatives with lower environmental impacts and (3) reduction in the construction stage impact (Figure 3) [91].

Research on reducing embodied carbon in buildings concentrates on material efficiency, lightweight construction and component reuse [92]. The approaches include low-carbon binders, supplementary cementitious materials (SCMs) and recycled aggregates, alongside bio-based materials and optimized designs aimed at minimizing life cycle carbon intensity [92–94]. The efforts to decarbonize steel by recycling or shifting steel production processes have also been explored [94]. Although local sourcing, waste reduction and energy-efficient construction can further reduce carbon [24,83,90], the industry faces notable barriers—economic, legislative, cultural and technical—that hinder the adoption of low-carbon techniques [95–98].

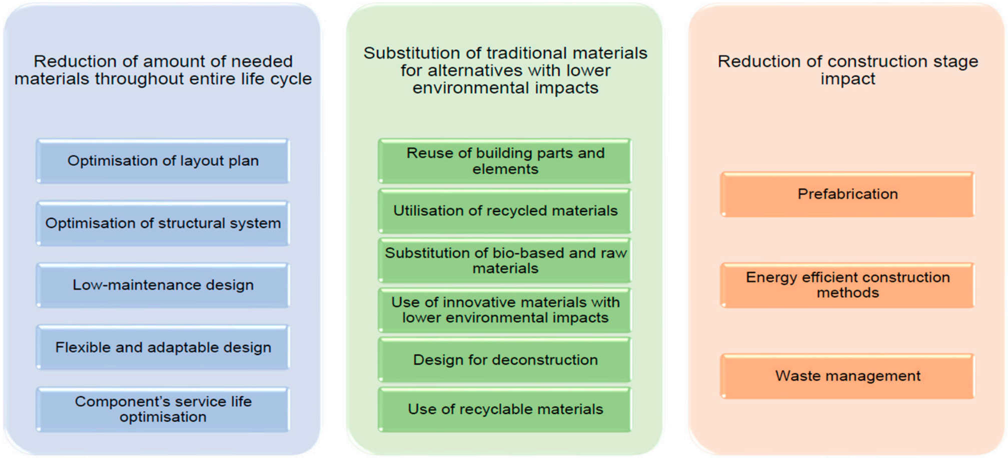


Figure 3. Various design strategies to reduce embodied carbon in buildings (IEA) [90].

A range of strategies have been proposed to decrease the carbon footprint of concrete construction, from reducing Portland cement clinker content to employing parametric design for structural optimization [99–102]. Studies highlight significant embodied carbon reductions (e.g., 20% in flat slabs, up to 51% in certain post-tensioned voided systems) [101–103]. Design parameters such as column spacing, slab depth and material selection can notably influence total embodied carbon [104–110]. Analytical models and design-assisting equations provide a basis for predicting and minimizing embodied carbon under varying loads, spans and deflection requirements [105,111–114]. Despite potential gains, the industry remains heavily reliant on GGBS and fly ash for reducing cement content, which are constrained resources [115,116]. To meet future demand, calcined clays and other emerging binders are under investigation for equal or greater carbon savings [117,118]. This study responds to the identified need for systematic structural optimization and enhanced concrete mix specifications, aligning with decarbonization roadmaps and carbon reduction hierarchies [28,80,119–121].

4.1. Material

Researchers have explored the optimization of concrete and steel properties, sectional dimensions and reinforcement designs to reduce embodied carbon. For instance, studies on flat slabs indicate that reducing spans and slab thickness significantly lowers emissions, with optimal designs commonly approaching the minimum feasible thickness [53,122]. Adopting high-strength concrete can cut carbon by 10–30% by decreasing material quantities and extending structural lifespans [123–125]. Studies also highlight the potential of knowledge-based systems, such as ontology and semantic web rules, for optimizing embodied carbon in specific structural components like columns [126].

In comparing steel–reinforced concrete composite columns under varying loads, one study found larger column dimensions more effective at reducing carbon under light loads, while adjusting steel shapes worked better for higher loads. Moreover, composite columns often outperform traditional reinforced concrete in carbon efficiency [127]. Heuristic algorithms applied to precast pre-stressed U-beams by varying geometry, reinforcement and material properties similarly demonstrated span-dependent carbon savings [128].

Overall, material selection is a key strategy for reducing embodied carbon [129,130]. Parametric design and genetic algorithms enable wide-ranging optimization of structural layouts, material usage and embodied carbon [49,101,102,131]. Meanwhile, material substitution—such as mass timber replacing steel or concrete—shows substantial carbon reduction potential, albeit limited by resource availability [35,132–134]. The use of supplementary cementitious materials (SCMs) and emerging alkali-activated materials (AAMs) also offers promising avenues for lowering the carbon footprint of concrete [135,136].

End-of-life management strategies, such as material reuse and recycling, are crucial for minimizing the overall environmental impact of buildings [102]. The importance of considering the entire life cycle of building materials, from extraction to disposal, is emphasized [130], highlighting the need for a holistic approach to embodied carbon reduction. The potential for carbon sequestration in timber structures is also discussed [137], highlighting the advantages of using wood as a building material. The use of lightweight panels as an alternative to masonry walls is also investigated [130], 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 [77,101].

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 not only reduces CO_2 emissions but also enhances concrete's long-term strength, durability, and resistance to chemical attack. Furthermore, it decreases permeability, contributing to improved structural performance and a reduced environmental footprint. These effects are shown in Table 2 [138].

Table 2. Effect of Portland cement replacement with fly ash on embodied carbon of concrete [24].

Concrete Grade	**Embodied Carbon (kgCO2e/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

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. These effects are shown in Table 3 [139].

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 [140].

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 [141].

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 [142].

Table 3. Emission factors of ready-mixed concrete (EFi) [143].

Concrete Mix With/Without Cement Substitute [a]	**Emission Factor for Each Strength Class (kgCO2e/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 in 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 in 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 [38,39]. 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 [48]. 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 [39].

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 [47]. 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 [10].

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 [144]. 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 [48].

The possibility of optimizing concrete elements by considering a range of sectional dimensions and reinforcement designs according to an existing design code has been studied by several researchers. A set of design charts for concrete frame elements have been developed and slab depths listed, which give the minimum cost for each span based on a series of parametric designs [17]. Controlling the deflections of their designs by referring to BS EN 1992-1-1 [13] adjusted span-to-depth ratios, the authors also found that providing more reinforcement to further reduce the allowable slab thickness can reduce overall cost. A review of the 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 [145].

The optimization of steel-reinforced concrete frames or beams through adjustments in reinforcement arrangement and sectional dimensions was demonstrated using genetic algorithms [42,43,146]. With the proven savings of around 25–36%, their studies confirm that understanding the trade-off between sectional dimensions and reinforcement may be a promising approach to optimizing the 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 [147]. 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 [148]. A parametric variation in 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 [27].

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 [149]. 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 [150]. The integration of FEA into life cycle assessments (LCAs) allows for the evaluation of embodied carbon across design alternatives, ensuring sustainability-focused decision making [142,151]. Machine-learning techniques have also been integrated into FEA workflows, streamlining the design process and enabling the rapid identification of low-carbon solutions [152].

Finite Element Modeling (FEM) is a robust numerical approach widely employed for analyzing reinforced concrete structures due to its capability to simulate complex interactions between concrete and reinforcement under various loading and boundary conditions. In FEM analysis, concrete is discretized into small meshed elements (Figure 4a) to accurately capture stress distribution and deformation. The reinforcement, typically modeled as embedded steel elements, interacts directly with concrete mesh elements, representing cohesive and integral structural behavior (Figure 4b). The accuracy of FEM results largely depends on appropriate mesh density, particularly in critical regions experiencing high stress gradients. Additionally, boundary conditions, such as fixed or hinged supports, significantly influence structural response and must be accurately defined to ensure reliable modeling outcomes (Figure 4c). This comprehensive approach facilitates a deeper understanding of the structural performance and potential optimization of reinforced concrete elements [2].

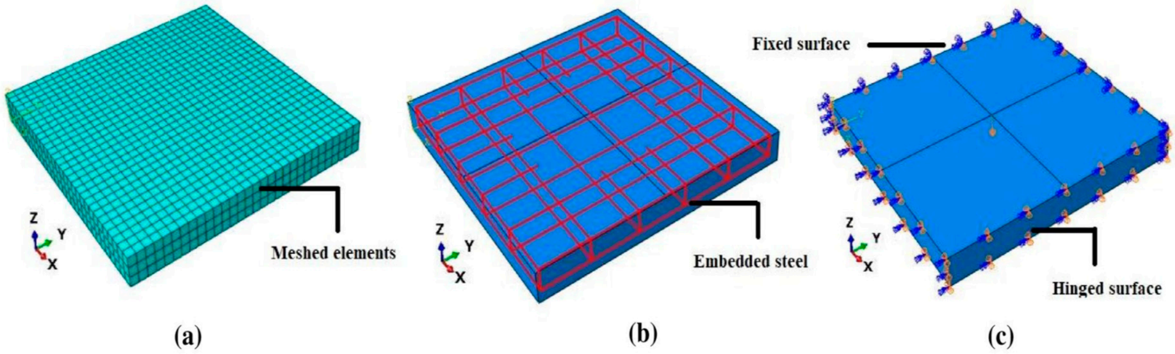


Figure 4. Geometry and boundary conditions of the finite element model of the two-way slab: (**a**) Meshing; (**b**) Embedded region constraint; (**c**) Boundary conditions [2].

Structural optimization techniques also include topology optimization, which determines the optimal material layout within a given design space under specific constraints [153]. This method leads to innovative designs that maximize structural performance while minimizing material use [154]. High-strength concrete is another effective strategy, enabling smaller cross-sections and reducing overall concrete volume while enhancing load-carrying capacity [155]. Additionally, composite materials, such as carbon-fiber-reinforced polymers (CFRPs), improve the strength-to-weight ratio of structural components, allowing for reduced concrete usage and increased durability, particularly in dynamic loading conditions [156,157]. 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 [158].

Research demonstrates that these techniques collectively reduce the embodied carbon of RC structures by 20–30% [159]. Case studies highlight their practical application, including material savings in bridge design [160] and precast concrete systems [161].

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 [68,162].

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 [163].

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 [164,165].

The use of real-time monitoring systems provides valuable data for assessing and managing deflections throughout a structure's life cycle. 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 [166,167].

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 [168,169].

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 [170]. The lighter weight of these slabs also reduces the overall load on the structure, contributing to more efficient designs [171].

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 [172].

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 [173].

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 esthetic appeal and sustainability [170].

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 the environmental impact [174,175].

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 [161]. 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 [161,176].

4.5. Use of Recycled Aggregate or Waste

The incorporation of recycled aggregates and industrial by-products into concrete provides a promising route to reduce carbon footprint and enhance sustainability. Recycled concrete aggregates (RCAs), sourced from demolition waste, can effectively replace virgin aggregates without compromising mechanical performance, although high replacement rates (>30%) may reduce compressive strength and increase shrinkage [177–179]. Other industrial by-products—e.g., crushed glass, plastic and rubber—improve durability, reduce landfill waste and curb greenhouse gas emissions [2,180,181]. Waste mineral powders further enhance strength and impermeability, offering an additional sustainable solution [182].

Despite these benefits, durability and contamination risks persist. RCA commonly features higher water absorption and porosity, increasing permeability and reducing resistance to chloride and carbonation [179,183,184]. If aggregates originate from contaminated sources, harmful substances (e.g., asbestos, metals) can degrade long-term performance or pose health risks [185,186]. Meanwhile, SCMs such as fly ash or slag face dwindling supply as coal-fired plants close, while their chemical properties can vary significantly, necessitating thorough quality control [99,187].

Environmental trade-offs also arise. Although waste utilization decreases landfill dependence, processing can be energy-intensive, and transportation over long distances may negate sustainability advantages [188]. The chemical variability of fly ash, FC3R and other by-products—sometimes shifting 15–40% in key oxide content—further complicates consistent concrete performance [189,190]. Supply chain disruptions and volatility in the pricing of materials can hamper large-scale adoption [191,192]. Regulatory limits on recycled content percentages, insurance concerns and a general preference for risk-averse approaches frequently impede broader use [193].

Nevertheless, technological innovations offer pathways to mitigate these concerns. Surface treatments (e.g., carbonation curing) can cut water absorption by up to 50%, while advanced sorting methods enable the production of recycled aggregates with more uniform properties [194]. Adopting performance-based specifications rather than strictly prescriptive standards can bolster the acceptance of recycled materials. These developments underscore the potential of recycled aggregates and industrial by-products to contribute meaningfully to sustainable construction when combined with robust quality control, strategic supply chain planning and supportive policies.

5. Analysis of the Embodied Carbon in Various Floor Systems

The comparison of embodied carbon based on the major types of floor systems shown in Figure 5 examines the environmental impact of various flooring designs, specifically focusing on greenhouse gas emissions throughout their lifecycle. With sustainability becoming a paramount priority in the construction industry, understanding the embodied carbon contributions of different floor types is essential for architects, builders, and policymakers aiming to mitigate environmental impacts. 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.

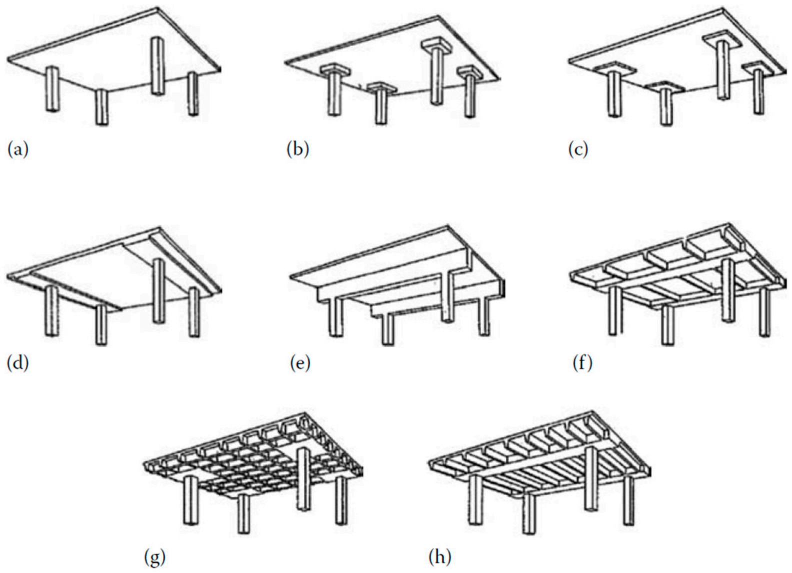


Figure 5. The major types of floor systems: (**a**) Flat plate; (**b**) Flat plate with column capitols; (**c**) Flat plate with drop panels; (**d**) Band beams; (**e**) One-way beam and slab; (**f**) Skip joist system; (**g**) Two-way joist slab; and (**h**) Standard joist system [195].

In concrete structures, the floor plays a vital role in influencing total embodied carbon due to its material composition and design [196]. 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 [28].

The choice of floor type in concrete structures significantly impacts the 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 [197]. 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 life cycle. Life cycle assessments (LCAs) help compare the emissions from different floor types, enabling informed, sustainability-focused design decisions. The study emphasizes performance-based approaches for sustainable concrete floor design [198].

Several researchers have discussed the differences in environmental and economic performance of the available floor systems. Flat slabs are generally considered economical for spans up to 8 or 9 m, while post-tensioned flat slabs are regarded as cost-effective for spans extending up to 12 or 13 m. However, although span ranges are provided where various floor systems demonstrate economic efficiency, no specification is given regarding which system is the most economical for a given span within these ranges [17]. The embodied carbon of several slab types was compared for a range of spans, and it was observed that waffle slabs were optimal for all viable spans, with hollow-core slabs having the second-lowest embodied carbon for spans longer than 7 m. 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 m [199]. 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 [200]. 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 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 [201]. A case study demonstrated that voided slabs could achieve a reduction in embodied carbon compared to an equivalent solid concrete floor solution [202]. 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 [203].

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 [168].

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 on foundations and other structural elements. Studies highlight the material and cost efficiencies achieved through slab optimization for membrane action [204].

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 the possibilities for modern construction [156].

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 [159].

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 [205]. 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 [206].

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 [207].

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 [208]. 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 [69].

5.1. Flat Slab

Flat slabs are a reinforced concrete floor system consisting of a flat (Figure 6), continuous slab supported directly by columns without the use of beams [197,209]. 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 [69]. Replacing cement with supplementary materials like fly ash or GGBS can further lower the embodied carbon footprint by up to 25% [210].

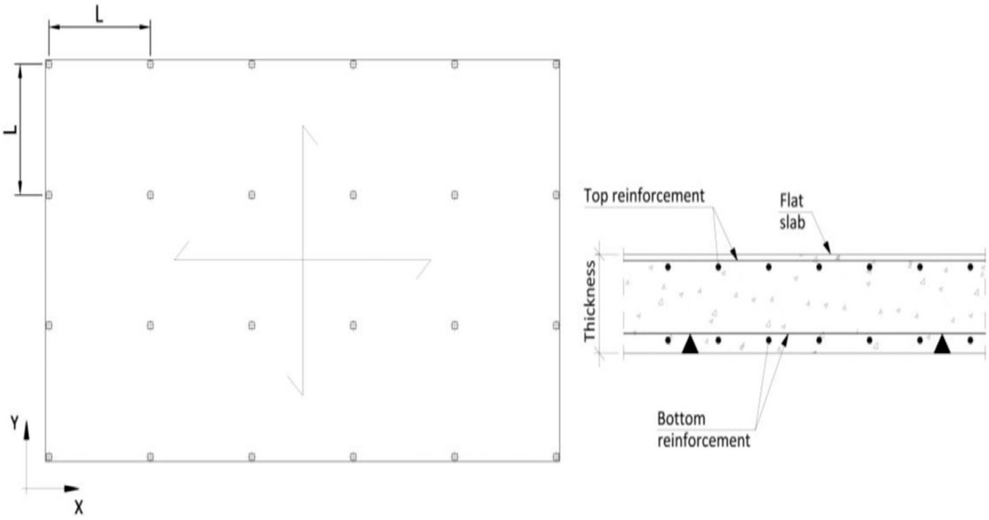


Figure 6. Details of flat slab [47].

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% [210].

Figure 7 illustrates the finite element model of a flat slab used for estimating nonlinear long-term deflection. It highlights the distribution of stresses, distinguishing clearly between tension and compression zones, along with detailed support conditions, which significantly influence the structural behavior under sustained loading [102].

For instance, a 200 mm thick flat slab with an 8 m span using standard concrete (C25/30) yielded 250 kg CO_2/m^2 [102]. In another study, a 250 mm thick flat slab over a 10 m span with high-strength concrete (C40/50) resulted in 350 kg CO_2/m^2 [197]. An optimized mix with supplementary cementitious materials (SCMs) for a 200 mm thick slab over 8 m reduced the embodied carbon to 180 kg CO_2/m^2 [211]. Lightweight concrete (C20/25) was used in a 200 mm thick flat slab with a 6 m span, achieving 220 kg CO_2/m^2 [212]. Lastly, a 300 mm thick flat slab over a 15 m span using standard concrete (C30/37) resulted in 450 kg CO_2/m^2 [213].

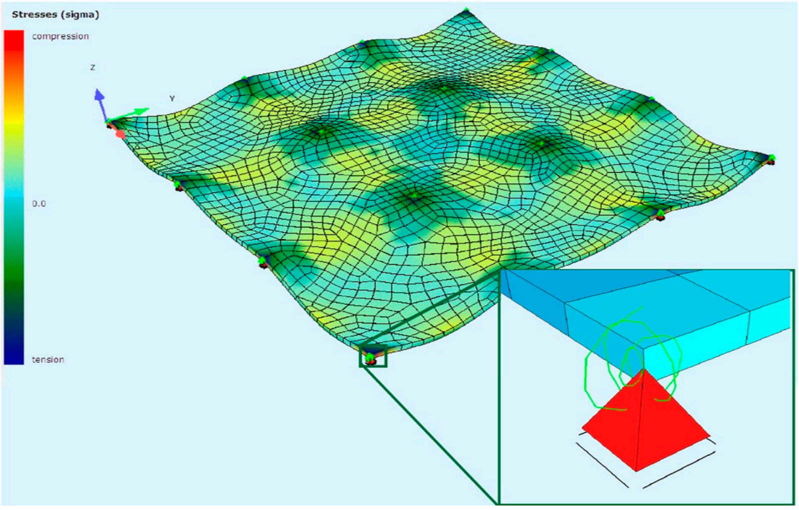


Figure 7. Finite element model of flat slab for estimating non-linear long-term deflection [102].

5.2. Beam and Slab

A 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 shown in Figure 8 [151]. 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 [197,209]. Optimization involves adjusting beam spacing and dimensions to reduce material use, achieving up to 15% reduction in embodied carbon [214].

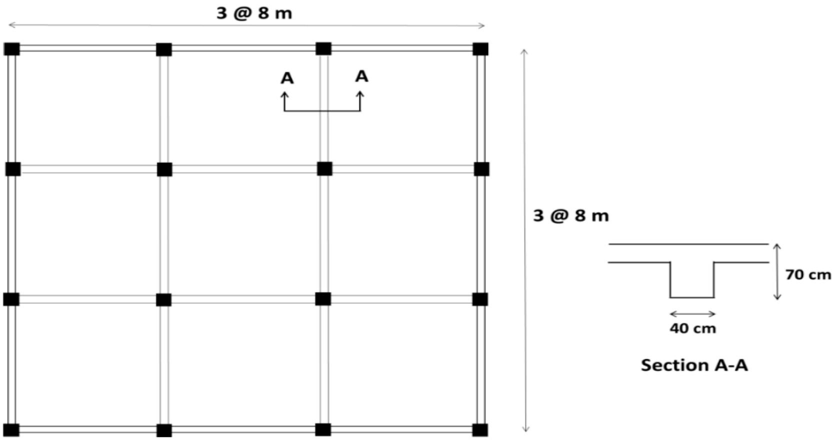
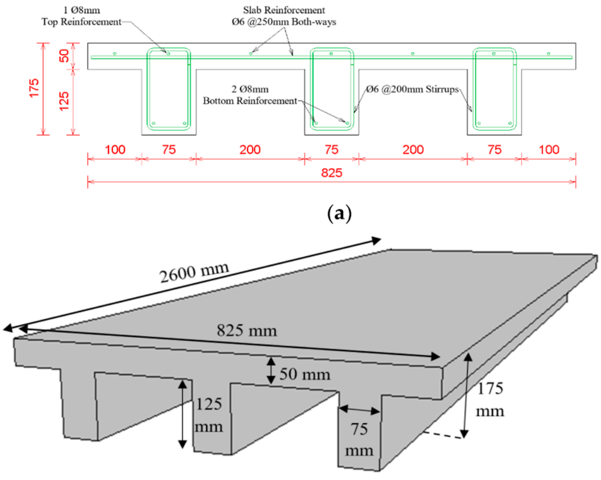


Figure 8. Representative building frame layout [159].

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 CO_2/m^2. For example, a 250 mm thick slab with a 6 m span using standard concrete (C25/30) yielded 320 kg CO_2/m^2 [215]. Additionally, a 300 mm thick slab over a 10 m span with high-strength concrete (C40/50) resulted in 450 kg CO_2/m^2 [216]. Lastly, a 300 mm thick slab over a 15 m span with standard concrete (C30/37) yielded 500 kg CO_2/m^2 [217].

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 columns shown in Figure 9 [197]. The ribs help reduce the overall concrete volume compared to a flat slab, leading to potential savings in material and embodied carbon [218]. 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% [218].



(**a**)

(**b**)

Figure 9. 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 [219].

Ribbed slabs are designed to reduce material usage while maintaining structural integrity, with the embodied carbon values ranging from 230 to 400 kg CO_2/m^2. For instance, a 300 mm deep ribbed slab with an 8 m span using standard concrete (C25/30) yielded 280 kg CO_2/m^2 [220]. A 300 mm deep ribbed slab spanning 12 m with conventional concrete (C30/37) resulted in 370 kg CO_2/m^2 [221]. Finally, a 300 mm deep ribbed slab with a 9 m span using recycled aggregates (C30/37) achieved 280 kg CO_2/m^2 [222].

5.4. Waffle

Waffle slabs (Figure 10) are known for their efficiency in material use, leading to lower embodied carbon values ranging from 180 to 350 kg CO_2/m^2. For example, a 300 mm waffle slab with a span of 9 m using standard concrete (C25/30) yielded 220 kg CO_2/m^2 [223]. Additionally, a 400 mm waffle slab over a 12 m span with high-strength concrete (C40/50) resulted in 340 kg CO_2/m^2 [224]. For instance, a 250 mm waffle slab with an 8 m span using recycled aggregates (C30/37) yielded 210 kg CO_2/m^2 [225]. In another study, a 300 mm waffle slab spanning 10 m with lightweight concrete (C20/25) achieved 300 kg CO_2/m^2 [226]. A 200 mm waffle slab with a 6 m span using standard concrete (C25/30) yielded 175 kg CO_2/m^2 [227]. Lastly, a 400 mm waffle slab over a 15 m span with high-performance concrete (C50/60) resulted in 350 kg CO_2/m^2 [228].

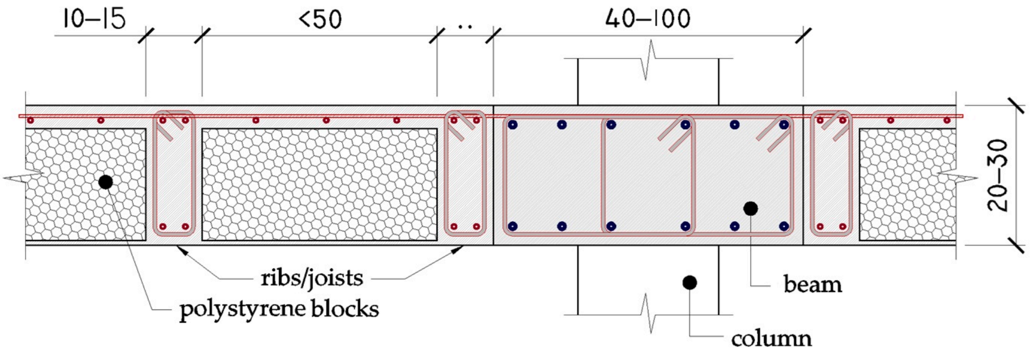


Figure 10. Typical detail of a wide beam and joisted slab used in Albania [229].

5.5. Post-Tensioned Concrete Floor

Post-tensioned slabs are designed to use less concrete and steel by pre-stressing the reinforcement. It is 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 as shown in Figure 11 introduces compressive forces into concrete, which improves its resistance to tensile stress and can result in thinner, more efficient floor structures columns [230]. This system is commonly used in large-span buildings, such as stadiums and bridges, where reduced self-weight is critical [231]. Post-tensioning can decrease material usage by 20–30%, significantly reducing the embodied carbon [211,232].

Post-tensioned concrete floors utilize high-strength steel tendons to enhance structural performance and reduce material usage. The embodied carbon for spans of 8–16 m with slab thickness between 150 mm and 250 mm, depending on the span and use, for concrete grades C40/50 [211] is approximately 180–300 kg CO_2/m^2.

For instance, a 200 mm thick post-tensioned slab with an 8 m span using standard concrete (C30/37) yielded 190 kg CO_2/m^2 [233]. Similarly, a 200 mm thick slab over a 10 m span with high-strength concrete (C40/50) resulted in 240 kg CO_2/m^2 [234]. In another example, a 300 mm thick post-tensioned slab with a 12 m span using recycled aggregates (C30/37) achieved 290 kg CO_2/m^2 [235]. Finally, a 300 mm thick slab spanning 15 m with lightweight concrete (C40/50) yielded 300 kg CO_2/m^2 [236].

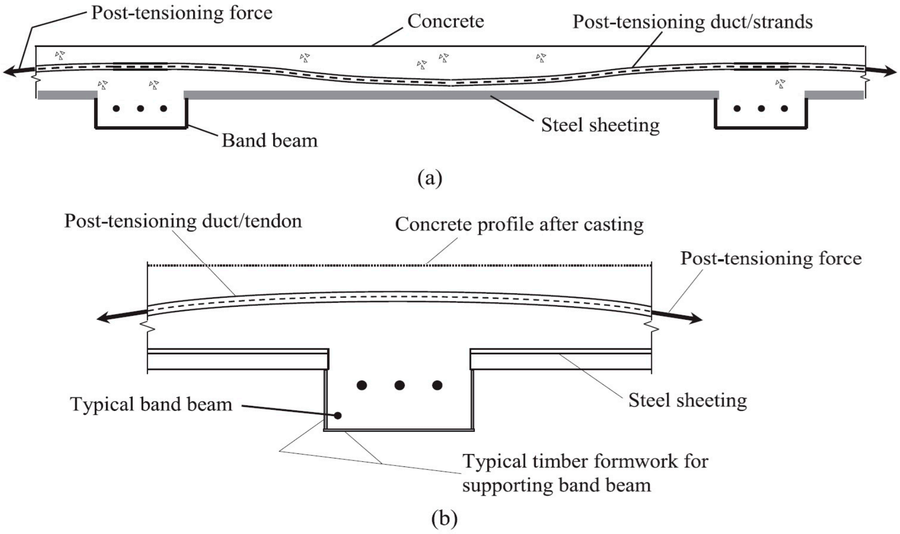


Figure 11. (**a**) Typical elevation of a post-tensioned composite slab supported by band beams; (**b**) Typical construction detail of profiled steel sheeting being supported via the band beam before concrete pour [237].

5.6. Hollow Core

Hollow-core slab is a precast, pre-stressed concrete floor system that consists of a series of parallel, hollow cores running the length of the slab shown in Figure 12 [218]. Hollow cores reduce the overall concrete volume, making hollow-core slabs a more sustainable option compared to solid slabs [197].

The embodied carbon for hollow-core slabs ranges from 180 to 320 kg CO_2/m^2. A 300 mm thick hollow-core slab with a 10 m 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 CO_2/m^2 [216,238]. Additionally, a 300 mm thick hollow-core slab with a 12 m span using standard concrete (C30/37) yielded 320 kg CO_2/m^2 [239]. A 200 mm thick hollow-core slab with a 5 m span using low-carbon concrete (C25/30) yielded 170 kg CO_2/m^2 [240].

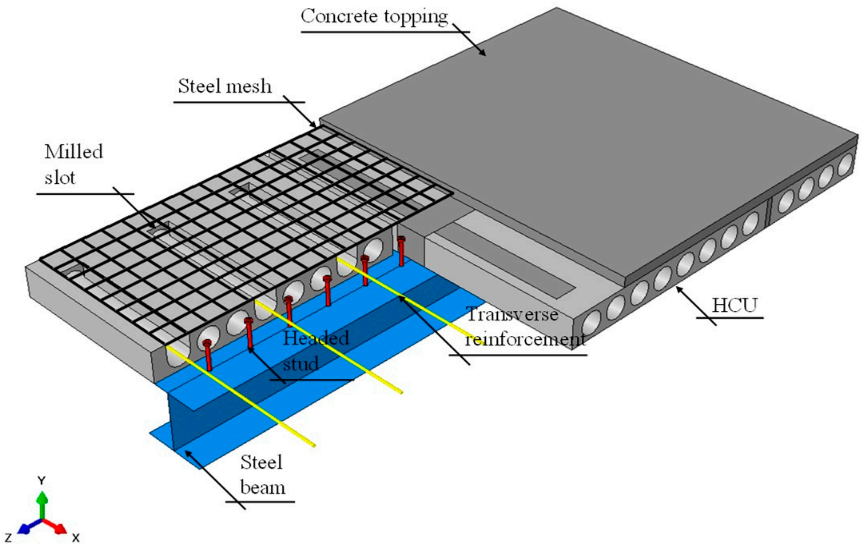


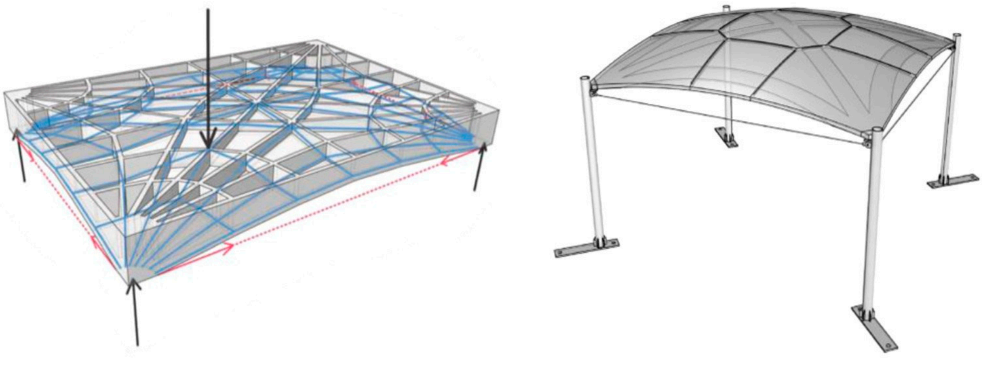
Figure 12. Parts of steel–concrete composite beams with a 150 mm thick hollow-core slab and 55 mm of concrete topping with a squared end [241].

5.7. Nervi-Style Slab

Nervi-style slab is a thin-shell concrete floor system, characterized by its curved, hyperbolic paraboloid shape [77]. 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 m span using standard concrete (C25/30) yielded 240 kg CO_2/m^2 [242]. Additionally, a 200 mm thick slab with an 8 m span using recycled aggregates (C30/37) yielded 230 kg CO_2/m^2 [243].

5.8. Arched Slab

Arched slab is a reinforced concrete floor system that features a curved, arched geometry [77] Figure 13 illustrates the effective distribution of loads, which can lead to a reduction in material usage [214]. 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 [77]. The embodied carbon values ranged from 200 to 380 kg CO_2/m^2. For instance, a 200 mm thick arched slab with a 6 m span using standard concrete (C25/30) yielded 200 kg CO_2/m^2 [244]. In another study, a 300 mm thick slab with a 9 m span using standard concrete (C40/50) yielded 260 kg CO_2/m^2 [245]. Furthermore, a 300 mm thick slab with a 10 m span using recycled aggregates (C30/37) yielded 310 kg CO_2/m^2 [246].



(a) (b)

Figure 13. (**a**) Funicular (arched) floors with external arch ties between columns investigated and (**b**) arched thin-concrete-shell floor plate investigated in [108].

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 ± 32 kgCO2e/m^2), followed by hollow-core slab systems (250 ± 47 kgCO2e/m^2). In contrast, beam and slab systems consistently showed the highest environmental impact (388 ± 77 kgCO2e/m^2). The hierarchical arrangement of systems based on mean embodied carbon values is as follows:

1. Post-tensioned concrete floor (247 ± 32 kgCO2e/m^2);
2. Hollow-core slab (250 ± 47 kgCO2e/m^2);
3. Waffle slab (263 ± 61 kgCO2e/m^2);
4. Arched slab (270 ± 58 kgCO2e/m^2);
5. Nervi-style slab (274 ± 47 kgCO2e/m^2);
6. Flat slab (286 ± 84 kgCO2e/m^2);
7. Ribbed slab (308 ± 59 kgCO2e/m^2);
8. Beam and slab (338 ± 77 kgCO2e/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 (0–6 m), medium spans (6–10 m) and long spans (10–15 m)—with each category demonstrating unique characteristics and performance metrics.

The variation in embodied carbon values across different span lengths for various roof types is illustrated in Figure 14, demonstrating the impact of structural design choices on embodied carbon emissions. As the span length increases, differences in the efficiency of each roof type become more pronounced, highlighting the role of material usage and structural optimization in minimizing embodied carbon. This data underscores the importance of selecting appropriate floor and roof systems to achieve sustainable design objectives in reinforced concrete structures.

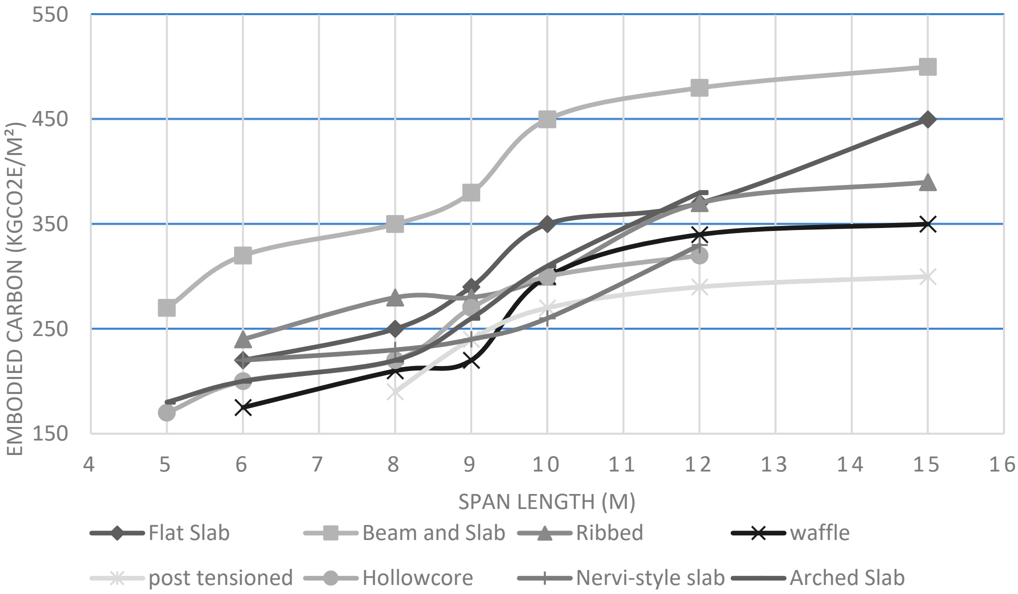


Figure 14. Comparing embodied carbon values based on span length in various roof types.

6.1.1. Short-Span Systems (0–6 m)

Analysis of short-span applications revealed that waffle slab systems demonstrated superior environmental performance with the lowest embodied carbon values (172 ± 8 kgCO2e/m^2), as shown in Table 4. 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 ± 13 kgCO2e/m^2), offering a good balance between simplicity and environmental impact.

Table 4. Amount of embodied carbon for short-span systems.

Floor Type	Embodied Carbon (kgCO2e/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

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

Notably, traditional beam and slab systems demonstrated the highest embodied carbon values (296 ± 19 kgCO2e/m^2) even in short spans, suggesting inefficient material utilization for these modest span requirements.

6.1.2. Medium-Span Systems (6–10 m)

The medium-span category revealed more pronounced differentiation between systems. Post-tensioned concrete floor systems emerged as the most efficient solution (245 ± 28 kgCO2e/m^2), closely followed by hollow-core slabs (247 ± 37 kgCO2e/m^2), as shown in Table 5. This performance advantage can be attributed to their optimized use of high-strength materials and efficient structural forms.

Table 5. Amount of embodied carbon for medium-span systems.

Floor Type	Embodied Carbon (kgCO2e/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

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 (200–400 mm), 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/m^2).

6.1.3. Long-Span Systems (10–15 m)

Long-span applications demonstrated the most significant variations in performance and the highest absolute embodied carbon values, as detailed in Table 6. Post-tensioned concrete floor systems maintained their environmental advantage (262 ± 39 kgCO2e/m^2), showing remarkable efficiency even at extended spans. This performance is particularly noteworthy given the structural challenges associated with longer spans.

Table 6. Amount of embodied carbon for long-span systems.

Floor Type	Embodied Carbon (kgCO2e/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

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

6.2. Mechanisms of Carbon Reduction

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

I. 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 pre-stressing forces.

II. 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.

III. Waffle Slab

- Creates efficient two-way spanning action;
- Removes concrete from low-stress zones;
- Maintains structural depth with minimal material;
- Provides inherent ceiling esthetics, reducing finishing materials.

IV. Arched Slab

- Utilizes natural compressive force paths;
- Minimizes tensile stresses through geometric optimization;
- Reduces material in non-critical areas;
- Benefits from structural form efficiency.

V. Nervi-Style Slab

- Optimizes material placement along force paths;
- Creates efficient ribbed patterns following stress lines;
- Combines esthetic and structural efficiency;
- Reduces material through biomimetic design principles.

VI. Flat Slab

- Simplifies formwork, reducing material waste;
- Provides direct force transfer to columns;
- Eliminates beam material volume;
- Allows for reduced floor-to-floor height.

VII. 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.

VIII. 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

7.1. Summary of Key Findings

This comprehensive analysis of eight concrete floor systems across varying spans yielded several significant conclusions with important implications for sustainable construction practices:

I. **System Selection Impact:** The choice of the floor system has a substantial impact on the embodied carbon, with variations of up to 40% between the best- and worst-performing systems. Post-tensioned concrete floor systems consistently demonstrated superior environmental performance across all span ranges (247 ± 32 kgCO2e/m^2), followed closely by hollow-core slab systems (250 ± 47 kgCO2e/m^2).

II. **Span-Dependent Performance:** Span length emerged as a critical factor in environmental impact, with all systems showing increased embodied carbon as spans increased. However, the rate of increase varied significantly between systems:

- Short spans (0–6 m): Waffle slab systems showed the lowest embodied carbon, followed by flat slabs. Their relatively thin profiles and material-efficient designs contributed to reduced carbon footprint.

- Medium spans (6–10 m): Post-tensioned and hollow-core slabs led the category, demonstrating the importance of high-strength materials and optimized structural forms in this range.
- Long spans (10–15 m): Although absolute embodied carbon values were highest in this range for all systems, post-tensioned and waffle slab systems still led in efficiency, highlighting their superior structural performance under extended spans.

III. **Traditional vs. Specialized Systems:** Conventional beam and slab systems consistently showed the highest environmental impact across all span ranges (338 ± 77 kgCO2e/m^2 overall), with this disadvantage becoming increasingly pronounced at longer spans (442 ± 57 kgCO2e/m^2 for 10–15 m spans).

IV. **Material Efficiency Mechanisms:** The superior performance of certain systems can be attributed to specific structural characteristics:

- Post-tensioned systems achieve efficiency through active force distribution and reduced concrete volumes;
- Hollow-core and waffle systems benefit from the strategic removal of non-structural concrete;
- Form-optimized systems (arched, Nervi-style) leverage geometric principles to minimize material use.

7.2. Comparative Analysis and Implications

The hierarchical arrangement of the systems based on mean embodied carbon values reveals clear performance tiers:

- Tier 1 (High Efficiency): Post-tensioned concrete floor (247 ± 32 kgCO2e/m^2) and hollow-core slab (250 ± 47 kgCO2e/m^2);
- Tier 2 (Moderate Efficiency): Waffle slab (263 ± 61 kgCO2e/m^2), arched slab (270 ± 58 kgCO2e/m^2) and Nervi-style slab (274 ± 47 kgCO2e/m^2);
- Tier 3 (Lower Efficiency): Flat slab (286 ± 84 kgCO2e/m^2), ribbed slab (308 ± 59 kgCO2e/m^2) and beam and slab (338 ± 77 kgCO2e/m^2).

This tiered performance has significant implications for the construction industry's carbon reduction efforts. Our analysis indicates that simply switching from a beam and slab system to a post-tensioned system could reduce the embodied carbon by approximately 27% on average, representing a substantial environmental benefit without requiring radical changes in construction methodology.

The performance gap between the systems widens with increasing span lengths, suggesting that system selection becomes increasingly critical for larger structural applications. For long-span applications (10–15 m), the embodied carbon difference between the best- and worst-performing systems reaches 180 kgCO2e/m^2 (a nearly 69% increase), highlighting the significant environmental impact of system selection decisions in larger projects.

8. Future Research

8.1. Comprehensive Cost–Carbon Correlation

Deeper Integration with Economic Analysis: While embodied carbon is increasingly recognized as a key metric for sustainability, the initial and long-term economic viability of low-carbon floor systems continues to drive decision making in the construction industry. Future research should focus on detailed cost–carbon trade-off analyses, identifying where investments in lower-carbon materials and design approaches yield both environmental and financial benefits.

Life Cycle Costing (LCC) Tools: Incorporating LCC models—covering material production, transportation, construction, maintenance and end of life—would help practitioners compare the total costs of different systems alongside their carbon footprints, leading to more holistic decision-making frameworks.

8.2. Long-Term Durability and End-of-Life Considerations

Performance Under Realistic Conditions: Extended service life studies under varying climatic, loading and usage conditions can reveal the long-term carbon "payback" of certain designs. Systems that initially require more resources may prove more sustainable if they outlast alternatives or require fewer repairs.

End-of-Life Recycling and Reuse: Investigating the strategies for reusing high-strength materials (e.g., pre-stressed tendons, steel reinforcement) and recycling concrete or composite materials can substantially reduce the embodied carbon over the life cycle. Research into novel methods—such as advanced crushing and sorting technologies—would be particularly valuable.

8.3. Innovative Materials and Fabrication Techniques

High-Performance and Low-Carbon Binders: Beyond conventional Portland cement, low-clinker cements, geopolymer concretes and supplementary cementitious materials (e.g., fly ash, slag) offer the pathways to lower embodied carbon. Further exploration of these materials' mechanical and durability properties will help bridge the gap between lab-scale research and wide-scale industry adoption.

Prefabrication and Automation: Advances in off-site manufacturing and robotic fabrication can enhance material consistency, reduce waste and streamline transportation. Investigating how design choices—for instance, panel shapes or integrated reinforcement—can be optimized for prefabrication may lead to lower-carbon solutions across various span ranges.

8.4. Parametric and Computational Optimization

Design Space Exploration: Parametric modeling and genetic algorithms can systematically explore a wide range of geometric and material configurations to uncover highly efficient, low-carbon floor designs. Automating iterative analyses (e.g., structural, cost and carbon evaluations) enables rapid evaluation of thousands of configurations, guiding designers toward optimal solutions.

Building Information Modeling (BIM) Integration: Integrating embodied carbon assessments directly into BIM platforms allows real-time feedback during the design phase. Research on seamless BIM-LCA workflows can help practitioners make immediate, data-driven adjustments to reduce carbon footprint.

In conclusion, this study demonstrates that optimizing floor system selection based on span requirements can significantly reduce embodied carbon in construction. The findings highlight the importance of moving beyond traditional system selection criteria to incorporate environmental performance as a primary consideration in structural design decisions. By implementing the recommendations outlined in this study and pursuing the identified research directions, the construction industry can make substantial progress toward reducing its carbon footprint while maintaining structural performance and functionality. As building regulations increasingly focus on whole-life carbon, the insights from this research provide a valuable foundation for developing more sustainable concrete floor solutions across diverse applications and span ranges.

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