Journal of Building Engineering 95 (2024) 110220

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Full Length Article

Designing for climate neutrality: Evaluation of reinforced-concrete slab systems in regard to emission reduction targets

Tânia Feiri [a,*], Sebastian Kuhn [a], Udo Wiens [b], Marcus Ricker [a]

[a] *Chair of Structural Concrete, TU Dortmund University, August-Schmidt-Straße 8, 44227 Dortmund, Germany*
[b] *German Committee for Structural Concrete, Budapester Straße 31, 10787 Berlin, Germany*

ARTICLE INFO

Keywords:
Reinforced concrete floor slabs
Greenhouse gas emission reduction targets
Sustainable structural design
Sustainable materials
Climate neutrality

ABSTRACT

To tackle the emergencies of climate change, Germany has pledged to become greenhouse gas neutral by 2045. In the context of such commitment, the German Committee for Structural Concrete (DAfStb) – a German expert body for structural concrete – has been developing a technical guideline, which proposes a set of annual reduction targets (by means of reduction classes) for limiting the embodied greenhouse gas emissions of structural systems. Previous research work suggests that opportunities for the mitigation of greenhouse gas emissions are higher during early design stages. However, the complexity that is typically involved in early decisions means that designing for reduced, or even minimal, emissions without loss of structural performance remains challenging for design practices. While the introduction of emission reduction targets for structural systems is a positive initiative for the promotion of more sustainable concrete construction, it might bring new and unexpected impacts for design practices. In this paper, the introduction of the emission reduction targets proposed in the new DAfStb guideline are investigated and their implications to practitioners are discussed. To this, two commonly-designed floor slab systems are evaluated in the context of a typical office/ residential multi-storey building by varying the design approach as well as the span width, loading conditions, concrete strength classes and cement compositions. The findings suggest that the combination of CO_2-efficient cements with optimised design approaches offers the largest potential for emissions savings and enables longer target-compliant spans widths. Nonetheless, from 2030 onwards, the use of more conventional slab systems, as cast-in-situ slabs, for long span widths might become challenging. While reframing conventional practices might be required, opportunities for the introduction of innovative materials and solutions might emerge.

1. Introduction

It is widely acknowledged that the sustainability of any human activity is a matter of major importance. The construction sector is no exception. The sector represents around 40 per cent of Europe's energy demand with 80 per cent of it being generated by fossil fuels (e.g., [1]). The major contributors to these demands are the construction materials as well as the heating, cooling, and lighting requirements for buildings and infrastructure. It is a fact that the use of natural resources for construction (in terms of mass) represents one of the biggest challenges regarding resources consumption (e.g., [2]). Worldwide, the heavy dependence of the

---

* Corresponding author.
E-mail addresses: tania.feiri@tu-dortmund.de (T. Feiri), sebastian.kuhn@tu-dortmund.de (S. Kuhn), udo.wiens@dafstb.de (U. Wiens), marcus.ricker@tu-dortmund.de (M. Ricker).

https://doi.org/10.1016/j.jobe.2024.110220
Received 10 November 2023; Received in revised form 10 June 2024; Accepted 13 July 2024

construction sector on materials is increasingly being blamed for the depletion of natural resources and environmental pollution. This has increased the pressure on the sector to become more resource efficient and, thus, reduce the amount of greenhouse gas emissions (e.g., [1–5]). To encourage the construction sector reducing greenhouse gas emissions, worldwide commitments for decarbonisation need to increase in both scale and pace [3]. In this respect, the whole Europe is trying to achieve the climate neutrality goal by 2050. With the amendment to the "Climate Change Act 2021" (in German: *Bundes-Klimaschutzgesetz*) [6], the German Federal Government intends to tighten climate regulations and, by 2045, enshrine in law the goal for greenhouse gas neutrality across multiple individual sectors, namely building, energy and transport.

Despite being recognised as a major challenge to the sector, climate-neutral concrete construction is perceived to be possible (e.g., [3,7]). To this, the participation of the entire value chain is required, namely investors, clients, planners, practicing engineers, contractors and representatives of building supervisory authorities, among others [7]. Also expert bodies are urged to take action. By being aware of this need, the German Committee for Reinforced Concrete (in German: *Deutscher Ausschuss für Stahlbeton e.V.*, DAfStb) – a German expert body for the promotion of best practices of structural concrete construction – has been involved in multiple initiatives to encourage the adoption of more sustainable approaches. One of such initiatives is the dissemination of the guideline "Principles of Sustainable Construction with Concrete" (in German: *"Grundsätze des nachhaltigen Bauens mit Beton"*) [8] (also known as *GrunaBau*). This guideline establishes the principles of sustainable, resource-efficient and climate-friendly construction with concrete and aims at promoting the adoption of more sustainable decision-making processes on the construction of steel-reinforced concrete structures (e.g., residential, administration or event buildings, shopping centres, industrial halls, among others). The *GrunaBau* guideline is also perceived as a preparation for a possible sustainability certification and demonstrates how sustainable design and construction can be carried out while complying with already existing rules of the sector [9]. Complementary to the *GrunaBau*, the DAfStb has also introduced other relevant documents as, for example, [9,10].

When planning for structural construction, opportunities for resources and material savings are highest at the conceptual design stage (e.g., [3–5]). Depending on the particular circumstances of a structural project, designers can influence their decisions to a certain extent by adopting good engineering practices [3]. Yet, more than ever, such decisions should include aspects of resource efficiency and climate protection [7]. Opportunities for the mitigation of greenhouse gas emissions during early design stages depend on choices regarding individual design configurations (e.g., loading conditions and geometric considerations, such as span width), materials properties (e.g., concrete strength class and cement mixture composition), alongside the selected design approaches (e.g., [4,5,7,11]). Nonetheless, structural design decisions that aim at reducing greenhouse gas emissions while guaranteeing the safety and functional performance of a structural component or system remain arduous to designers.

Over the last few years, attempts to better understand and overcome such difficulties have been made through numerous studies comparing the environmental performance of distinct configurations of load-bearing components or systems over their lifetime as, for example, [11–16], just to list a few. In Germany, the DAfStb has been preparing a new technical guideline entitled "Greenhouse gas-reduced load-bearing structures made of concrete, reinforced concrete or prestressed concrete" (In German: *"Treibhausgasreduzierte Tragwerke aus Beton, Stahlbeton oder Spannbeton"*) [17]. This guideline is applicable to concrete, reinforced concrete, prestressed concrete and other modern structural solutions such as components made of fibre-reinforced concrete. Here, the basic requirements and measures for the construction of load-bearing structures were established in harmony with national and international references for greenhouse gas reduction targets. Additionally, the guideline is in line with other well-known sustainability certification systems as, for example, the Leadership in Energy and Environmental Design (LEED), the Sustainable Building Quality Label (in German: *"Qualitätssiegel Nachhaltiges Gebäude"*, QNG-Siegel) or the German Sustainable Building Council (in German: *"Deutsche Gesellschaft für Nachhaltiges Bauen"*, DGNB). This document [17] was idealised to include four parts: Part 0 defining the basic requirements for greenhouse gas-reduced structures considering embodied (or embedded) carbon emission values (carbon emissions for the operation phase are outside the scope of this guideline); Part 1 addressing the design of floor slab systems; Part 2 dealing with vertical structural components and Part 3 giving recommendations for the design of foundations and basements. Yet, so far, only Parts 0 and 1 have been developed [17]. It should be highlighted here that the emission reduction targets proposed in Part 0 are aligned with the provisions of the Federal Government set in the amendment to the "Climate Change Act 2021" (in German: *Bundes-Klimaschutzgesetz*) [6].

While the introduction of emission reduction targets for structural systems is a positive initiative for the promotion of more sustainable concrete construction, it might bring new and unexpected impacts for structural design practices. In this paper, the potential implications of the emission reduction targets proposed in the new DAfStb guideline on structural design practices are investigated. To this, two commonly-designed floor slab systems are evaluated in the context of a typical office/residential multi-storey building by varying the design approach as well as the span width, loading conditions, concrete strength classes and cement compositions. Considering that the definition of such emission reduction targets is pioneering in structural design practices, the results of this investigation – and, ultimately, the validation of the proposed emission targets – are pivotal to reflect on the need to reframe conventional design practices and go above and beyond the provisions of structural codes.

This paper is organised as follows: Section 2 introduces the greenhouse gas emissions reduction targets and classes proposed in the new DAfStb guideline [17]. Section 3 gives an overview on the main characteristics of the floor slab systems addressed in this investigation and Section 4 describes the assumptions and configurations adopted for the evaluation of the respective greenhouse gas emissions of these systems. The results are presented and discussed in Section 5 and a reflection on the potential implications of such results on current structural design practices is given in Section 6. Finally, the main conclusions of this investigation are summarised in Section 7 next to a set of avenues identified for future research.

Table 1
Greenhouse gas target values $\alpha_{GWP,t}$ and allocation to greenhouse gas reduction classes TM_t for structures in residential, non-residential and office buildings [17].

TM_t	Calendar year	$\alpha_{GWP,t}$ [–]	Permissible emissions [kg CO_2-Eq./m^2_{BGF} [c]]	
			Residential	Non-residential
TM_{2020}	2020[a]	1.00	250	320
TM_{2024}	2024	0.75	188	240
TM_{2026}	2026	0.65	163	208
TM_{2028}	2028	0.56	140	179
TM_{2030}	2030	0.48	120	154
TM_{2032}	2032	0.42	105	134
TM_{2034}	2034	0.36	90	115
TM_{2036}	2036	0.31	78	99
TM_{2038}	2038	0.27	68	86
TM_{2040}	2040	0.23[b]	58	74
TM_{2042}	2042	0.14[b]	35	45
TM_{2044}	2044	0.05[b]	13	16
TM_{2046}	2046	0.00[b]	0	0

[a] Reference year.

[b] From 2040, the values are reduced linearly according to the requirements of the “Climate Change Act 2021” [6]. To implement the reduction path, additional measures are required.

[c] BGF: Square metre of floor area (gross).

2. Greenhouse gas emissions reduction targets and classes for floor slab systems

As discussed in Section 1, the greenhouse gas emission reduction targets $\alpha_{GWP,t}$ postulated by DAfStb in “Greenhouse gas-reduced load-bearing structures made of concrete, reinforced concrete or prestressed concrete” [17] aim to guide practitioners to design for minimal greenhouse gas emissions. Part 0 of the DAfStb guideline proposes a set of emission reduction targets defined according to the design year; the emission reduction targets gradually decrease from 2020 (the reference year) to the end of 2045, when the emission neutrality target is planned to be attained (Table 1). For calculation purposes, the year of 2046 is considered. It should be emphasised here that the emission reduction targets proposed in the DAfStb guideline concerns only the embodied (or embedded) carbon emissions (i.e., the total greenhouse gas emissions generated during the production and transportation of goods, from the extraction of raw materials to the manufacturing process and final delivery to the consumer). The carbon emissions generated during the operational phase (i.e., usage phase) of a structure are left outside the scope of the DAfStb guideline – and, thus, outside the scope of this investigation.

For each target year, the emission reduction target $\alpha_{GWP,t}$ is associated to an emission reduction class TM_t, (Table 1). These targets are calculated according to Eq. (1):

$$\alpha_{GWP,t} = 1 - \beta_{\mathrm{CO}_{2,red}}^{\,t-2020} \tag{1}$$

with $\beta_{\mathrm{CO}_{2,red}}$ being 0.07 (corresponding to 7 per cent) reduction to be annually paid and t [–] corresponding to the year of the building application.

Part 1 of the DAfStb guideline provides means to assess the greenhouse gas reduction targets $\alpha_{GWP,t}$ for structural components through the relationship proposed in Eq. (2):

$$\frac{\sum GWP_{Eco,i}/\mathrm{m}^2}{\sum GWP_{Ref,i}/\mathrm{m}^2} \le \alpha_{GWP,t} \tag{2}$$

with $GWP_{Eco,i}$ being the Global Warming Potential (GWP) expressed in kilogram CO_2-equivalent ([kg CO_2-Eq.]) for a structural component i, considering the emissions from the Production Stage (Module A1: Raw material supply, Module A2: Transport and Module A3: Manufacturing) and from the End-of-Life Stage (Module C3: Waste Processing and Module C4: Disposal) according to DIN EN 15804 [18]. The term $GWP_{Ref,i}$ concerns the reference GWP in kg CO_2-Eq. for a structural component i.

For floor slab systems, the parameter $GWP_{Ref,i}$ depends on the span width S_i and is given through Eqs. (3) and (4):

$$GWP_{Ref,i} = 40 \cdot \sqrt{S_i}\,\left[\frac{\mathrm{kg\,CO_2-Eq.}}{\mathrm{m}^2}\right],\quad 0\ \mathrm{m} \le S_i \le 10\ \mathrm{m} \tag{3}$$

$$GWP_{Ref,i} = 126.5\,\left[\frac{\mathrm{kg\,CO_2-Eq.}}{\mathrm{m}^2}\right],\quad 10\ \mathrm{m} < S_i \le 15\ \mathrm{m} \tag{4}$$

with S_i being the span width [m] for a reference structural component i. To define and calibrate Eqs. (3) and (4), the DAfStb conducted a detailed analysis on 45 distinct floor slab systems. The results of this analysis is not included in this investigation; yet, it can be consulted in [17]. Note that slab spans longer than 15 m are unconventional in building structures.

Fig. 1 illustrates the proposed emission reduction targets for floor slab systems, which are defined according to the span width S_i.

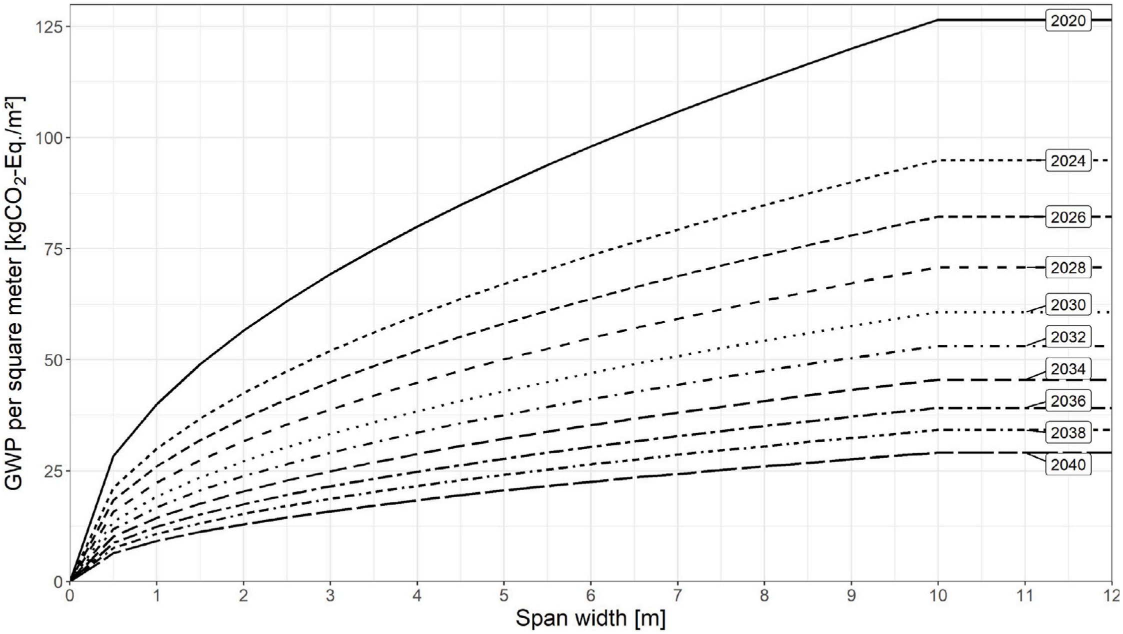

Fig. 1. Greenhouse gas emission reduction targets for floor slab systems according to [17].

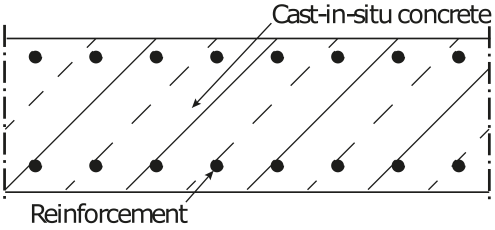

Fig. 2. Schematic section of cast-in-situ slabs.

At the time of publishing this manuscript, a revised version of the new DAfStb guideline [19,20] no longer connects the greenhouse gas reduction classes TM_t to target values for specific years. Instead, the greenhouse gas reduction classes are linked to a percentage reduction value TM_t (in percentage) compared to a reference determined for the year 2020. Irrespective of this revision, the results and discussions addressed in this manuscript remain fully valid.

3. Brief overview on the floor slab systems considered in this investigation

3.1. Introduction

Among all parts of a building, floor slab systems (except when applied as foundations) are those with the greatest impact on the building sustainability. In multi-storey buildings, floor slab systems tend to demand significant material amounts. Hence, when considering scale effects, floor slab systems have a large potential for material and resources savings and, therefore, for more resource-efficient structures [21]. Nonetheless, the quantification of the environmental impacts associated to the use of these systems is case dependent and is related to the overall structural complexity of a building [7,22]. The main influencing parameters are the type and geometry of both building and structural systems, their constitutive components and main construction materials [7] as well as the construction processes [23].

Slabs made of reinforced-concrete are among the most common solutions utilised for floor systems (e.g., [21,23]). These can be cast-in-situ (also known as cast-in-place or built on site), partially prefabricated (or precasted), or completely prefabricated.

In this investigation, two floor slab systems are addressed: Cast-in-situ solutions and precast prestressed hollow core slabs. In Germany, while cast in-situ slabs tend to be the conventional solution for the slab systems of multi-storey buildings, hollow core slabs have been gradually considered as an alternative solution. The main characteristics of these systems are described in the following sub-sections.

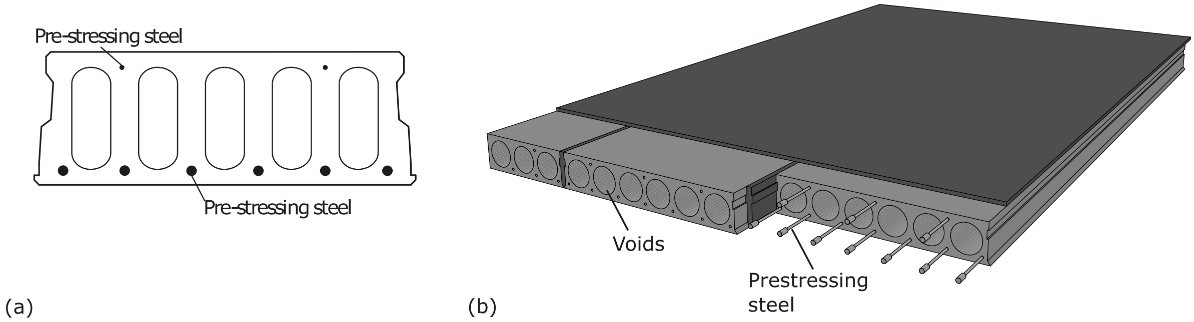

Fig. 3. Precast prestressed hollow-core slabs: (a) Schematic section; (b) Schematic 3D representation.
Source: Adapted from [24].

3.2. Cast-in-situ floor slabs

Cast-in-situ is a technology of building construction where the structural components are cast-in-place through the use of removable formwork in which the reinforcement has been laid beforehand. The formwork is dismantled once the concrete has hardened. The main advantage of cast-in-situ solutions (scheme in Fig. 2) is seen in the monolithic effect with relatively small slab thickness as well as in the simple production of statically indeterminate structures [25]. The load-bearing reserves, which are often present due to a higher degree of static indeterminacy, prove to be particularly advantageous in the event of a local overload. With slab thicknesses varying between 0.18 m and 0.30 m, loosely-reinforced spans can be built up to 6.5 m with unidirectional load transfer (i.e., one-way spans) and up to 8 m with bidirectional load transfer (i.e., two-way spans) [25].

Cast-in-situ slabs are perceived as economical and versatile slab systems. For example, they enable complex shapes, changes during construction and reconstruction and have high fault-tolerance mainly due to the possibilities offered by modern formwork technology.

The main disadvantages of these slabs are their large self-weight, their labour intensive requirements on site and high dependency on external conditions (e.g., weather conditions) when concreting large areas is needed. In addition, depending on the complexity of the slab system layout, quality control of cast-in-situ solutions can be challenging.

It should be highlighted that cast-in-situ slabs can be ribbed and incorporate prestress. Such structural configurations enable significant longer span widths than conventional cast-in-situ slabs. These configurations were left outside the scope of this investigation.

3.3. Precast prestressed hollow core floor slabs

Initially developed in the 1960s as deck elements for industrialised buildings [26], precast prestressed hollow core slabs are, nowadays, more frequently applied as a slab solution for multi-storey buildings. These slabs are monolithic prestressed or reinforced elements with a constant overall depth divided into an upper and a lower flange, linked by vertical webs in a symmetrical manner (scheme in Fig. 3). They are based on the principle of reducing the self-weight by putting voids in the centre of the cross-section.

Intended for uniaxial load transfer, only prestressed strands (or wires) are installed as reinforcement with an immediate bond in the longitudinal direction. Further reinforcement is usually not provided. The slabs and voids are normally manufactured through extrusion or slip-forming. After reaching a concrete strength between 25 N/mm^2 and 30 N/mm^2, the slabs are cut according to the desired span length. The degree of prefabrication of these systems is, thus, very high [27]. The slabs are laid “dry” on site and the joints between the elements are filled with concrete. Afterwards, the slabs can be immediately loaded.

Compared to other floor slab systems, hollow core floor slabs have higher flexural and shear capacities [24]. Since prestress is introduced into the cross-section, they exhibit excellent crack controllability, which is advantageous for deflection control under service loads [24]. Additional benefits are the quick assembly on site, low labour-intensive requirements and consistent quality (ensured by strict quality control measures adopted during the manufacturing process). Furthermore, the reduced self-weight is perceived as an advantage since it lowers material and transportation costs. The amount of concrete and steel needed to produce these slabs is significantly reduced compared to cast-in-situ solutions. Thus, these systems are perceived as more environmentally efficient than cast-in-situ slabs. Also positive is the fact that the high formwork requirements normally enable smoother surfaces compared to other floor systems.

In terms of disadvantages, the hollow and light design can cause some negative effects in terms of sound insulation, limit the layout of the buildings to rigid shapes and introduce concerns about fire resistance capability (e.g., [24,26,28]). Furthermore, according to [29], the main explicit geometrical constraints of these systems refer to the cross-section geometrical variables defining the limits to web and flange thickness. Note that specific standards have been issued related to the structural behaviour of hollow core slabs, including the *fib* special design considerations for precast prestressed hollow core floors [30] and the European product standard EN 1168 [31]. For the design of these systems both documents act complementary to the provisions in DIN EN 1992-1-1+NA(D) [32–35] applicable in Germany. The costs are an additional constrain of hollow core slab systems, which tend to be more higher than those involved in the construction of conventional cast-in-situ solutions.

Table 2
Limit states and respective design approach considered in the investigation.

Limit states		Description	Design approach			
			1	2	3	4
ULS	1.	Bending design (sagging moment)	✓	✓	✓	✓
	2.	Bending design (hogging moment)	✓	✓	✓	✓
	3.	Limited redistribution of moment	✓	✓	✓	✓
	4.	Shear design	✓	✓	✓	✓
	5.	Shear design at the interface between concrete casts	✓	✓	✓	✓
	6.	Minimum reinforcement area	✓	✓	✓	✓
SLS	1.	Cracking control	✓	✓	✓	✓
	2.	Deflection control (limiting bending slenderness)	✓		✓	
	3.	Deflection control with direct calculation[a]		✓		✓

[a] For the pre-camber calculations in design approaches 2 and 4.

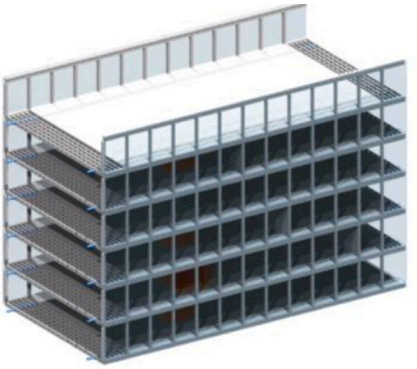

Fig. 4. Reference building from *"Stadtbaustein"* [10].

4. Design considerations and variables for parametric studies

4.1. General considerations

In this investigation, the exemplary building addressed in the DAfStb publication *"Stadtbaustein"* [10] (scheme in Fig. 4) was considered. The structure refers to a multi-storey building with a planned lifetime of 100 years. It should be mentioned that the *"Stadtbaustein"* contemplates two distinct configurations for the slab systems: (i) a flexible variant, whose system is prepared to withstand varying usage requirements over the building lifetime; therefore, this variant has an underlying sustainable principle and (ii) a standard variant, whose system is based on the adoption of conventional design solutions without much consideration for the lifetime variation of the usage requirements. The standard variant in the *"Stadtbaustein"* assumes that during the first 40 years, the building has an exclusive office function. After this time, the main structure is dismantled and a new structure shall be built to comply with the requirements for residential usage over 60 years. For the sake of this investigation, the geometric considerations of the standard variant were adopted.

The design calculations and the quantification of the greenhouse gas emissions were carried out in *R* [36], a programming language for statistical computing and graphical plotting.

4.2. Design approaches

One of the basic principles of sustainable structural engineering is to minimise energy and resource consumption and, simultaneously, comply with the provisions of modern structural codes. In this investigation, the limit state design methodology was adopted, where two principal criteria must be satisfied [37]: (1) ultimate limit states (ULS), which ensure that a structure is able to withstand the loads for which it is designed with an adequate factor of safety against collapse and guaranteeing the safety of the building occupants and/or the safety of the structure itself and (2) serviceability limit states (SLS), which ensure that during the normal working conditions, a structure satisfies a set of specific requirements, in this case, regarding cracking, durability and deflection.

The limit states addressed in this investigations are listed in Table 2, which were defined according to the provisions of DIN EN 1992-1-1+NA(D) [32–35]. Note that transient and accidental design situations were excluded from the analysis (i.e., only persistent design situations were considered).

For the analysis, a limited redistribution of the support moment was considered up to a certain limit and the exact redistribution value was iteratively determined. In this context, redistribution means decreasing bending moments above the support and increasing bending moments in mid-spans where the distribution of moments remains in equilibrium with the applied loads. Modifying the design bending moments may be helpful in reducing the required reinforcement, especially at locations of high bending moment. Note that the moment redistribution needs to be limited within the plastic rotation capacities of the sections. Here, the rotation capacity was determined through the simplified procedure prescribed in DIN EN 1992-1-1+NA(D).

As listed in Table 2, a minimum reinforcement area was defined (according to the provisions of DIN EN 1992-1-1+NA(D)) to prevent early ductile failure. Additionally, the maximum height x of the compression zone was limited to less than $0.45d$. For the SLS under the service loads, the crack width was limited to 0.4 mm.

As also listed in Table 2, the deflection control was considered by limiting bending slenderness for the design approaches 1 and 3 described below. For the design approaches 2 and 4, the deflection control was carried out with direct estimation, which was used for the calculation of the pre-camber. It shall be stressed here that DIN EN 1992-1-1+NA(D) allows to use a pre-camber to compensate for some of (or all) the deflection. Yet, any upward deflection incorporated in the formwork should not generally exceed the relationship given by span/250. In this investigation, the pre-camber was limited by the relationship span/250 and by the deflection of the permanent loading.

For the sake of this investigation, the following design approaches were established:

- Design approach 1: Regular
  Design with verification of deflection through limitation of bending slenderness which governs the slab thickness. For cast-in-situ slabs, the design includes the rearrangement of the hogging moment and its calculation at the support edge. In terms of concrete and cement configurations, this approach uses the configuration 1 for cast-in-situ slabs and configuration 3 for precast prestressed hollow core slabs (see Section 4.3.2).
- Design approach 2: Maximum camber
  Design using the constructive possibility given by the maximum permissible camber in combination with the assumptions of design approach 1. Here, the deflection is directly calculated. This approach uses the concrete and cement configuration 1 for cast-in-situ slabs (see Section 4.3.2).
- Design approach 3: Modern cement
  Design using the same considerations of approach 1 in combination with a modern cement mixture (i.e., CO_2-efficient cement). In terms of concrete and cement configurations, this approach uses the configuration 2 for cast-in-situ slabs and configuration 4 for precast prestressed hollow core slabs (see Section 4.3.2).
- Design approach 4: Maximum camber and modern cement
  Design using the considerations of approaches 2 and 3: Maximum permissible camber in combination with a modern cement mixture (i.e., CO_2-efficient cement). This approach uses the concrete and cement configuration 2 for cast-in-situ slabs (see Section 4.3.2).

When the verification of ULS and SLS was not satisfied either the slab thickness or the amount of reinforcing steel was increased.

For the design of prestressed hollow core slabs, the data from the *Ketonia* manufacturer (in German: *Spannbeton-Fertigdecke Typ VMM -VSD*) [38] was used. For the verification, the moments and shear forces were determined and compared to the capacity of the *Ketonia* slabs.

4.3. Design variables

4.3.1. Geometric considerations and loading conditions

For the system configuration, a three-field slab system was considered. For the analysis of cast-in situ slabs, a continuous three-field slab was adopted. For the analysis of precast hollow core slabs, three independent single span slabs were idealised. In this investigation, the outer spans varied on intervals of 0.50 m ranging between 4 m and 12 m. The length of the inner span was considered constant. Fig. 5 offers a schematic illustration of these considerations.

In terms of loads, an additional permanent load of $2\,kN/m^2$ was defined together with the self-weight of the respective slab. For the live loads, two types were assumed: $3.2\,kN/m^2$ and $5\,kN/m^2$, which resulted in two distinct load configurations:

- Load configuration 1: $2\,kN/m^2$ + Self-weight of the slab + $3.2\,kN/m^2$
- Load configuration 2: $2\,kN/m^2$ + Self-weight of the slab + $5.0\,kN/m^2$

The loads were combined according to the provisions of DIN EN 1992-1-1+NA(D) [32–35] to obtain the maximum bending moment in the field (i.e., sagging moment) and the maximum hogging moment at the support.

4.3.2. Material considerations

For this investigation, the following concrete and cement configurations were idealised (Table 3):

- Concrete and cement configuration 1: Concrete compressive strength C30/37 with a conventional cement mixture.
- Concrete and cement configuration 2: Concrete compressive strength C25/30 with a modern cement mixture (i.e., CO_2-efficient cement).

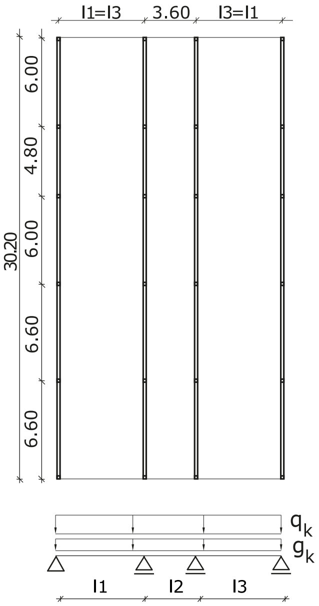

Fig. 5. Geometric configuration of the floor slab systems (schematic).

Table 3
Concrete and cement configurations.

Configuration	Reference for environmental information (EPD)	Concrete class	Cement mixture	Composition (mean values[a] in percentage)				
				Cement	Water	Aggregate	Fly ash and mineral powder	Aggregate (others)
1	[42]	C30/37	Conventional[b]	13.3	6.9	77.15	2.6	0.1
2	[43]	C25/30	Modern[c]	12.4	7.5	77.5	2.6	0.1
3	[44]	C45/55	Conventional[b]	15.65	6.55	75.55	2.15	0.15
4	[44]	C45/55	Modern[c]	15.65	6.55	75.55	2.15	0.15

[a] The mean values were calculated from a range of values given in the respective EPD.

[b] Conventional mixture composition [45]: 70 % Portland cement clinker, 18 % slag sand, 5 % limestone, 0.5 % fly ash, 0.5 % burnt slate, and 6 % calcium sulphate.

[c] Modern mixture composition (e.g., CEM II/C in [46]): 47 % Portland cement clinker, 28 % slag sand, 19 % limestone, and 6 % calcium sulphate.

- Concrete and cement configuration 3: Concrete compressive strength C45/55 with a conventional cement mixture.
- Concrete and cement configuration 4: Concrete compressive strength C45/55 with a modern cement mixture (i.e., CO_2-efficient cement).

It should be emphasised that the conventional cement mixture assumed in this investigation represents the average characteristics of the most common mixtures utilised in Germany for office/residential building typologies. An alternative composition, denoted here as a modern cement, refers to a more environmentally-friendly mixture (in this case, a mixture CEM II/C was considered). Reference values for both cement mixture configurations were taken from different Environmental Product Declarations (EPD) and DAfStb booklets, whose references are given in Table 3. Table 4 summarises the design approaches described in Section 4.2 alongside the concrete and cement configurations adopted for the analysis of each floor slab system.

For the reinforcing steel, the type B500 was considered [39]. For the prestressing steel, the types St 1470/1670 (e.g., [40]) and St 1570/1770 (e.g., [41]) were used. The effect of formwork in the environmental performance of the slabs was neglected since its influence is considered minor. If only a small amount of reinforcement was needed, reinforcement mats (up to 5.24 cm^2/m) were selected. For reinforcement needs between 5.24 cm^2/m and 15 cm^2/m, the largest reinforcement mat (5.24 cm^2/m) was adopted together with additional rebars; for reinforcement needs greater than 15 cm^2/m, only rebars were considered.

4.4. Quantification of greenhouse gas emissions

Instruments that enable the comparison of products based on economically sound and objective indicators are required to promote market competition towards ecologically responsible targets [48]. In this context, several mechanisms are available as

Table 4
Design approaches and concrete configurations considered for the analysis of each slab floor system.

Slab system	Design approaches				Concrete and cement configurations			
	1	2	3	4	1	2	3	4
Cast in-situ	✓	✓	✓	✓	✓	✓		
Precast prestressed hollow core	✓		✓				✓	✓

Table 5
Quantification of greenhouse gas emissions (GWP).

Material	References for environmental information	Modules			GWP
		A1-A3	C3	C4	
Concrete and cement :					(kg CO_2-Eq./m^3 concrete)
Configuration 1	Table E5 in [47] (based on [42] and [45])	✓	✓	✓	219
Configuration 2	Table E5 in [47] (based on [43] and [46])	✓	✓	✓	158
Configuration 3	Table E5 in [47] (based on [44] and [45])	✓	✓	✓	286
Configuration 4	Table E5 in [47] (based on [44] and [46])	✓	✓	✓	229
Steel:					(kg CO_2-Eq./t steel)
Reinforcing steel	Table B1 in [17]	✓			683.4
Prestressing	Table B1 in [17]	✓	✓	✓	1813.5

Environmental Product Declarations (EPD), a third-party verified document that aims to quantify and communicate environmental information about a product based on its entire lifecycle. Consequently, comparisons between products of the same category are possible [49] by taking into consideration their full value chain. Normally, they include environmental information that is detailed according to the respective lifecycle phase (i.e., detailed information by means of modules). Such phases and modules are in line with the provisions of DIN EN 15804 [18] and DIN EN ISO 14025 [50], a document that establishes the principles for the use of environmental information. Typically, the environmental information concerns material extraction (Modules A1–A3), manufacturing (Modules A4–A5), usage stage (Modules B1–B7), end-of-life (Modules C1–C4) and the potential benefits and loads beyond the lifecycle (e.g., recycling possibilities) (Module D). Table 5 describes the environmental information of the materials utilised in the considered floor slab systems. For steel, the environmental information was taken from the lifecycle assessment datasets available in the DAfStb guideline [17] (reference year 2020). It should be stressed here that the values accounting for the steel emissions at the end-of-life stage are, in this case, included within Module C of concrete emission values.

5. Results and discussion

5.1. Permissible span widths in regard to emission reduction targets

5.1.1. Cast-in-situ floor slabs

Fig. 6 shows the greenhouse gas emissions of cast-in-situ floor slabs varying according to span widths. The figure also displays the emission reduction targets specified in the DAfStb guideline [17]. As listed in Table 4, all the four approaches described in Section 4.2. were considered for the design and evaluation of cast-in-situ slabs.

For both live load configurations, the design approach 1 (regular design) leads to the highest greenhouse gas emissions in comparison to the remaining design approaches. By 2024, spans longer than 10 m designed for a live load configuration of 5 kN/m^2 no longer comply with the emission reduction targets. Likewise, spans longer than 10.5 m designed for a live load configuration of 3.2 kN/m^2 are higher than the specified targets. By 2028, spans longer than 5.5 m using a live load configuration of 5 kN/m^2 and longer than 6.5 m using a live load configuration of 3.2 kN/m^2 do not comply with the reduction targets established for this year. From 2030 onwards, cast-in-situ slabs designed with a live load configuration of 3.2 kN/m^2 with spans longer than approximately 4.5 m do not verify the established targets. For the live load configuration of 5 kN/m^2, the maximum-compliant span decreases to 4 m. As mentioned in Section 3.2, the maximum span of these slab systems is typically limited to values between 6.5 and 8 m [25]. In practice, this implies that the design of cast-in-situ slabs might start to face constraints from 2028 and be actually challenging from 2030.

The adoption of design approach 2 (maximum permissible camber) appears to bring additional benefits in comparison to the use of design approach 1. However, considering the permissible span designs described in [25] (6.5 m and 8 m), the first design challenges might occur by 2028, where spans longer than 7.5 m appear to be close to such physical limitations. Effectively, from 2030 onwards, spans longer than 5.5 m no longer meet the emission reduction targets for any of the live load configurations considered in this investigation.

The use of more CO_2-efficient cements in design approach 3 appears to enable slightly longer spans than with the use of the previous design approaches. The results indicate that spans longer than 10.5 m designed for a live load configuration of 5 kN/m^2 are no longer target compliant by 2026. By this year, the use of a live load configuration of 3.2 kN/m^2 enables the design of spans

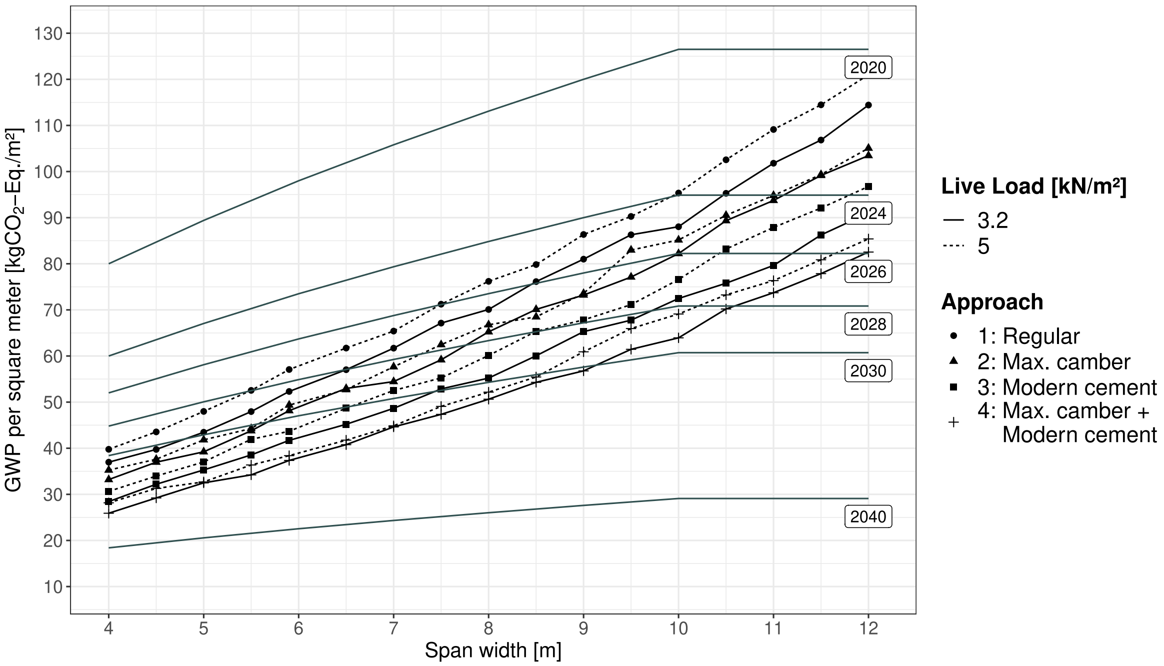

Fig. 6. Cast-in-situ floor slab systems: Greenhouse gas emissions in dependence of span width (span range: 4 m to 12 m).

up to approximately 11 m. The range of possible spans reduces sharply by 2030, where spans longer than 6.5 m for a live load configuration of 5 kN/m^2 or longer than 7.5 m for a live load configuration of 3.2 kN/m^2 register greenhouse gas emissions above the specified targets.

Finally, the adoption of design approach 4, which combines the maximum permissible camber with a CO$_2$-efficient cement, appears to enable a wider range of target-compliant spans. For both live load configurations, it appears to be possible to consider spans up to 12 m until 2026, which is higher than the typical span widths adopted for these systems. By 2030, the range of possible spans decrease to 8.5 m for a live load configuration of 5 kN/m^2 and to 9 m for a live load configuration of 3.2 kN/m^2, again above the common span widths.

5.1.2. Precast prestressed hollow core floor slabs

Fig. 7 displays the greenhouse gas emissions of precast prestressed hollow core slabs in dependence of span widths alongside the emission reduction targets specified in the DAfStb guideline [17]. As listed in Table 4, for the design of precast prestressed hollow core slabs, only the approaches 1 and 3 (see Section 4.2.) were considered.

With the design approach 1, spans longer than 11 m might be difficult to implement by 2028. By 2030, constrains associated with the use of hollow core slabs appear for spans longer than 6.5 m when these are designed with a live load configuration of 5 kN/m^2. For a live load configuration of 3.2 kN/m^2, target-compliant spans are possible up to 8.5 m. Note that even though relative small spans (i.e., between 4 and 6.5 m) appear to be possible by 2030, their greenhouse gas emissions are very close to the specified targets.

With the design approach 3, spans longer than 11 m no longer comply with the established emission reduction targets by 2028. No significant difference was identified between the results of both live load configurations. From 2030 onwards, spans longer than 6.5 m designed with a live load configuration of 5 kN/m^2 have higher greenhouse gas emissions than the established reduction targets. For a live load configuration of 3.2 kN/m^2, spans are possible up to 8.5 m.

5.2. Comparison of greenhouse gas emissions generated through different design approaches

5.2.1. Design approach 1: Regular

As listed in Table 4, the design approach 1 was considered for the design of both floor systems: cast-in-situ slabs and precast prestressed hollow core slabs.

Fig. 8 compares the greenhouse gas emissions of both slab systems when they are designed under the prepositions of approach 1 (regular design). From this figure, it can be seen that by 2030, relatively small spans – i.e., between 4 and 5 m – in both systems register minor differences between the respective emissions. For both live load configurations, spans of 4 m generate practically the same emissions, varying only marginally between 37 and 40 kg CO$_2$-Eq./m^2. Note that for spans between 4 and 5 m, the slab

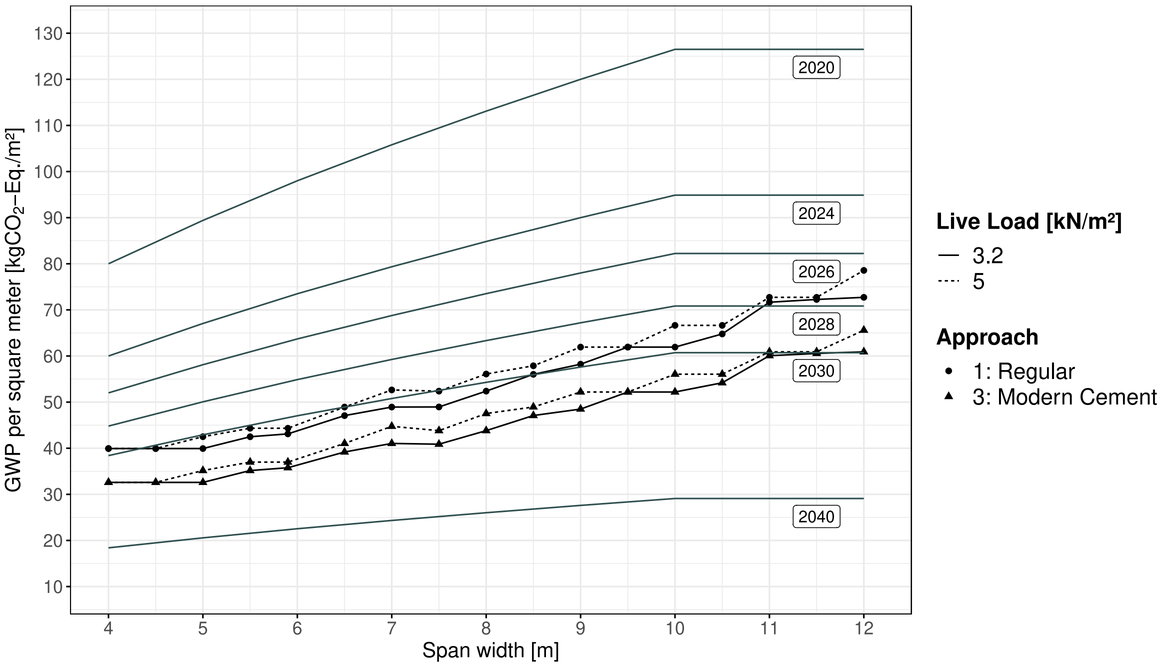

Fig. 7. Precast prestressed hollow core floor slab systems: Greenhouse gas emissions in dependence of span width (span range: 4 m to 12 m).

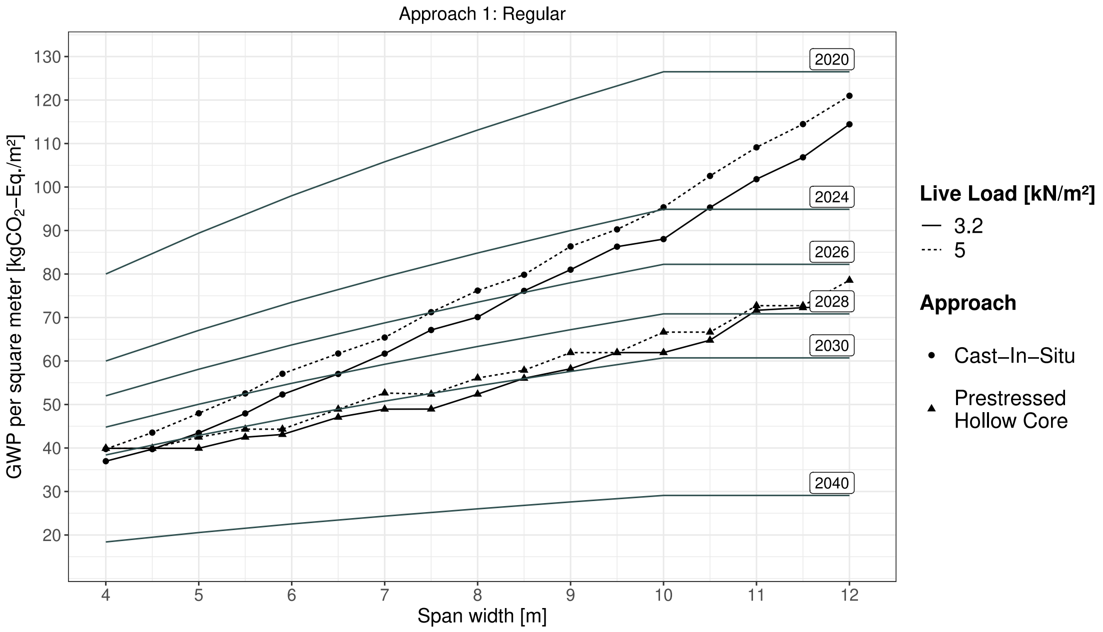

Fig. 8. Comparison of floor slab systems designed with approach 1 (regular design).

thickness of cast-in-situ slabs vary between 0.14 m and 0.18 m, whereas hollow core slabs for these spans can be designed with a thickness of 0.16 m.

These emissions vary only to a small extent for cast-in-situ spans of 5 m (slab thickness varying between 0.17 m and 0.19 m), with values ranging between 44 and 48 kg CO_2-Eq./m^2. For the same span width of 5 m, hollow core slabs can be designed with a thickness of 0.16 m, generating emissions ranging between 40 and 43 kg CO_2-Eq./m^2. This means that emission savings of around 8 per cent can be attained in comparison to cast-in-situ slabs when they are designed for a live load configuration of 3.2 kN/m^2 (Fig. 9) and of around 12 per cent when they are designed for a live load configuration of 5 kN/m^2 (Fig. 10).

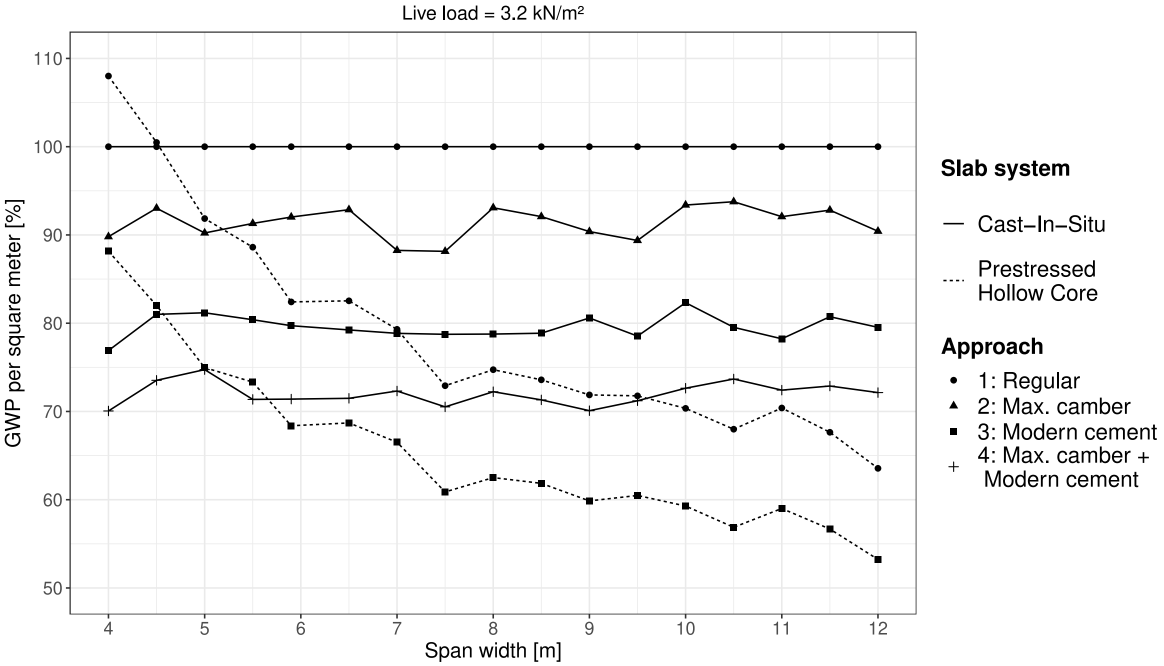

Fig. 9. Relative greenhouse gas emissions in percentage (normalised case: cast-in-situ slabs with design approach 1 for a live load configuration of 3.2 kN/m^2).

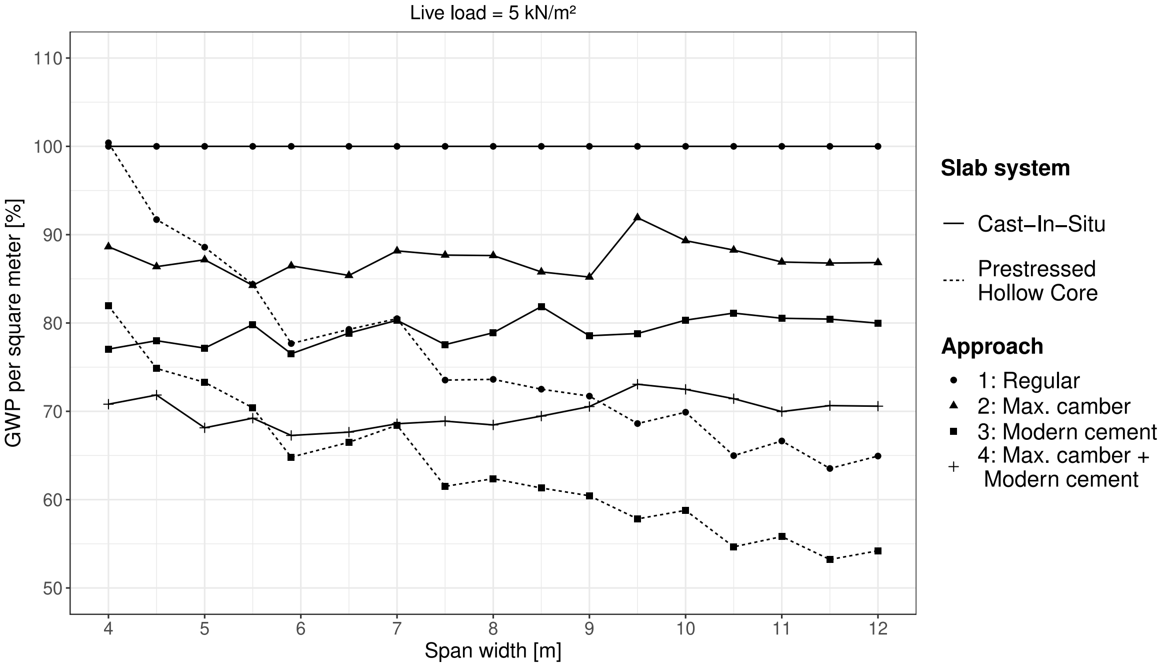

Fig. 10. Relative greenhouse gas emissions in percentage (normalised case: cast-in-situ slabs with design approach 1 for a live load configuration of 5 kN/m^2).

For increasing spans, the differences between the greenhouse gas emissions of both systems increase gradually. For spans of 7 m, for example, cast-in-situ slabs can be designed with thickness varying between 0.24 m and 0.25 m, registering emissions between 61 to 65 kg CO_2-Eq./m^2. In their turn, hollow core slabs can be designed with a thickness of 0.18 m, producing emissions revolving between 49 and 53 kg CO_2-Eq./m^2. In the case of hollow core slabs with spans of 7 m, the savings in terms of emissions are around 20 per cent independently of the live load configuration considered in the design (Figs. 9 and 10).

For spans of 8 m, the emissions of cast-in-situ slabs (slab thickness varying between 0.27 m and 0.29 m) revolve around 70 to 76 kg CO_2-Eq./m^2, while the emissions of hollow core slabs (slab thickness of 0.20 m) sit between 53 and 56 kg CO_2-Eq./m^2. For this span width, the relative emission savings are approximately 25 per cent for a live load configuration of 3.2 kN/m^2 (Fig. 9) and marginally higher – around 26 per cent – for a live load configuration of 5 kN/m^2 (Fig. 10).

As mentioned in Section 5.1.1, the maximum span of cast-in-situ slabs is typically limited to values around 6.5 and 8 m [25]; thus, no further comparison regarding this slab system is given in this section. However, from this analysis it is clear that hollow core slabs produce considerably fewer emissions than more conventional solutions, as it is visible in Figs. 9 and 10. For relatively small spans – i.e., between 4 and 5 m –, the differences between the emissions produced by each system are less stringent, independently of the live load configurations considered in the design.

5.2.2. Design approach 2: Maximum camber

As listed in Table 4, the use of design approach 2 was only considered for the analysis of cast-in-situ slabs. Hence, as in the previous section, the discussion of the results is limited to spans up to 8 m.

Fig. 9 indicates that cast-in-situ slabs spans of 4 m designed for a live load configuration of 3.2 kN/m^2, can have a thickness of 0.12 m. These enable relative emission gains of around 10 per cent in comparison to the same-span slabs designed under the prepositions of design approach 1. For a live load configuration of 5 kN/m^2, the relative gains yielded by spans of 4 m (same slab thickness of 0.12 m) are slight higher: around 12 per cent (Fig. 10).

Spans of 5.5 m designed for a live load configuration of 3.2 kN/m^2 under the prepositions of approach 2, result in a thickness of 0.16 m. Here, the gains are around 8 per cent in relation to the same span of 5.5 m designed with approach 1 (Fig. 9). For a live load configuration of 5 kN/m^2, spans of 5.5 m (slab thickness of 0.16 m) designed with approach 2 enable gains of 15 per cent in comparison to the same span slabs designed under the prepositions of design approach 1 (Fig. 10).

For spans of 7 m and for both live load configurations (slab thickness varying between 0.20 m and 0.21 m), the relative emission savings resulting through the use of design approach 2 are around 12 per cent (Figs. 9 and 10).

Finally, a span of 8 m with a camber (slab thickness of 0.24 m) enables emission savings between 7 and 12 per cent, respectively for live load configurations of 3.2 kN/m^2 and 5 kN/m^2, in relation to the use of design approach 1 (Figs. 9 and 10).

5.2.3. Design approach 3: Modern cement

As listed in Table 4, the design approach 3 was considered for the design of cast-in-situ slabs and precast prestressed hollow core slabs.

Fig. 11 displays the greenhouse gas emissions of both floor slab systems designed under the prepositions of approach 3 (modern cement). This figure shows that cast-in-situ slabs with spans of 4 m can have a thickness varying marginally between 0.14 m and 0.15 m, respectively, for both live load configurations of 3.2 kN/m^2 and 5 kN/m^2, respectively. Slabs with such characteristics produce around 30 kg CO_2-Eq./m^2 (Fig. 11). In comparison to design approach 1, the use of modern cements in cast-in-situ slabs with spans of 4 m yields emission savings of 23 per cent for both live load configurations (Figs. 9 und 10). Regarding the emissions of hollow core slabs with spans of 4 m (slab thickness of 0.16 m), the values are somewhat higher than those generated by the same spans cast-in-situ slabs when they are designed under approach 3. These emissions are around 10 per cent higher for a live load configuration of 3.2 kN/m^2 (Fig. 9) and around 5 per cent higher for a live load configuration of 5 kN/m^2 (Fig. 10).

Cast-in-situ slabs with spans of 5 m can be designed with thicknesses of 0.17 m and 0.18 m for the live load configurations of 3.2 kN/m^2 and 5 kN/m^2, respectively. These slabs generate emissions between 35 and 37 kg CO_2-Eq./m^2 (Fig. 11). In comparison to design approach 1, the use of modern cements enables relative savings of around 19 per cent considering a live load configuration of 3.2 kN/m^2 (Fig. 9) and 23 per cent considering a live load configuration of 5 kN/m^2 (Fig. 10). With the design approach 3, hollow core slabs with spans of 5 m (slab thickness of 0.16 m) produce marginally lower emissions than those produced by the same span cast-in-situ slabs designed with this approach (Fig. 11). The savings are around 6 per cent for a live load configuration of 3.2 kN/m^2 (Fig. 9) and around 5 per cent for a live load configuration of 5 kN/m^2 (Fig. 10).

For spans of 7 m, emissions of cast-in-situ slabs (slab thickness varying between 0.25 m and 0.27 m) sit between 48 to 53 kg CO_2-Eq./m^2 (Fig. 11). These values represent around 20 per cent of savings relative to the use of design approach 1 (Figs. 9 and 10). With the same design approach 3, the emissions of hollow core slabs (slab thickness of 0.18 m) vary between 41 and 45 kg CO_2-Eq./m^2 (Fig. 11). Figs. 9 and 10 show that the differences to cast-in-situ slabs designed with approach 3 are around 12 per cent for both live load configurations.

The emissions of cast-in-situ slabs with 8 m (slab thickness of 0.28 m and 0.30 m) sit between 55 to 60 kg CO_2-Eq./m^2 (Fig. 11). These values represent around 22 per cent savings in relation to the use of design approach 1 (Figs. 9 and 10). With the same approach, the emissions of hollow core slabs (slab thickness of 0.20 m) vary between 44 and 48 kg CO_2-Eq./m^2 (Fig. 11). Figs. 9 and 10 show that the differences to cast-in-situ slabs (design approach 3) are around to 16 per cent for both live load configurations.

It is important to highlight here that when the emissions of hollow core slabs designed under the considerations of approach 3 are compared to cast-in-situ slabs designed under approach 1, the relative emission savings are even more stringent. For example, a span of 5 m of hollow core slabs designed with approach 3 for a live load configuration of 3.2 kN/m^2 has 25 per cent less emissions than a span of 5 m of cast-in-situ slabs designed with approach 1. These gains increase with the span width. For example, for spans of 7 m, the gains can go up to 32 per cent and for spans of 8 m, the gains increase to approximately 37 per cent.

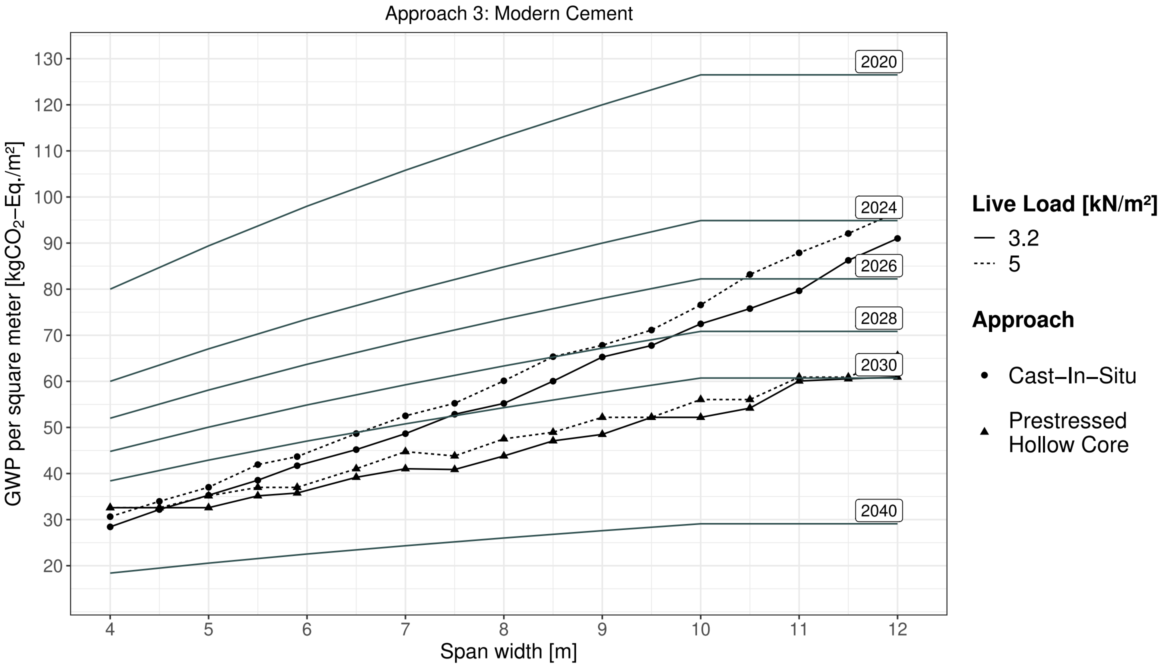

Fig. 11. Comparison of floor slab systems designed with approach 3 (modern cement).

5.2.4. Design approach 4: Maximum camber and modern cement

As listed in Table 4, this approach was only considered for the design of cast-in-situ slabs.

Fig. 9 indicates that for both live load configurations (3.2 kN/m^2 and 5 kN/m^2), cast-in-situ slabs with spans of 4 m designed with approach 4 can have a thickness of 0.12 m. When the slabs are designed with approach 4, the emission gains are around 30 per cent in comparison with the same-span slabs designed under the prepositions of approach 1 (Fig. 10).

For a span of 5 m designed for a live load configuration of 3.2 kN/m^2 under the prepositions of approach 4 (slab thickness of 0.15 m), the gains are around 25 per cent in relation to the same span slab designed with approach 1. For a live load configuration of 5 kN/m^2, the same span of 5 m designed with approach 4 (slab thickness of 0.15 m) yields gains of 32 per cent in relation to the use of approach 1.

For a span of 7 m designed for a live load configuration of 3.2 kN/m^2 under the prepositions of approach 4 (slab thickness of 0.22 m), the gains are around 27 per cent in relation to the same span slab designed with approach 1 (Fig. 9). For a live load configuration of 5 kN/m^2, the same span of 7 m designed with approach 4 enables gains of 31 per cent in relation to approach 1 (Fig. 10).

For a span of 8 m and a slab thickness of 0.24 m, the emission gains are exactly in the same range as those described for spans of 7 m (Figs. 9 and 10).

6. Practical implications of the results

From Section 5, a couple of overarching considerations can be derived. First, the results indicate that designing conventional solutions, as cast in-situ floor slabs, may become increasingly challenging over the years, especially when the design of long spans is required. By 2030, spans longer than approximately 4 m that are designed under regular provisions for a live load configuration of 5 kN/m^2, no longer meet the emission reduction targets proposed in the new DAfStb technical guideline [17]. The potential to save emissions in structures increases when additional efforts are made by combining the design approach with more environmentally-friendly materials (e.g., CO_2 efficient cement mixtures). Such combination also enables longer target-compliant spans.

Second, despite of modern cements and concretes compositions being already available in many developed nations, they are still not the preferred materials among practicing engineers and other stakeholders, who tend to be risk averse and favour more conventionally-accepted solutions (i.e., design preferences go to widely available materials and solutions with high cost predictability).

Third, based on the results of this investigation, it can be argued that designing to satisfy the “basic” provisions of structural codes might no longer be sufficient to comply with the specified emission reduction targets, and ultimately, reach the carbon-neutrality proposed at the government level (see Section 1).

Consequently, it is highly likely that the adoption of more technologically-advanced materials as well as extra efforts on design optimisation approaches may lead to additional project and building costs. Note that, to some extent, these outcomes – and consequently, implications to structural design practices – have been previously acknowledged in former investigations. A set of barriers to the adoption of sustainable design practices was already identified by Ahn et al. in [51] by mentioning that stakeholders tend to maintain their current practices of design, construction, operation, maintenance, and demolition despite potential innovations related to sustainability that they could adopt. Other existing barriers that prevent the adoption of sustainability-oriented practices include the high cost for sustainable materials and products and the first cost premium of sustainable design and construction [51]. The perceived initial cost premium barrier may make practicing engineers hesitant to implement sustainable solutions in their investments. Also, the lack of both knowledge and financial incentives may contribute to sustainability objectives to not be efficiently accounted for in most practical structural projects [3].

To tackle these challenges, the engineering community possibly needs to reframe well-established practices. This need seems to support the premise that for more sustainable development of the built environment, a shift of paradigm might be required regarding how engineering structures are designed (e.g., [3]). Yet, the results of the current investigation suggest that practicing engineers might need to be encouraged to achieve performances that go above and beyond the provisions of structural codes in order to move towards the proposed emission reduction targets – and ultimately, reach the climate neutrality goal.

Nonetheless, it is pivotal to highlight that the introduction of emission reduction targets may also encourage structural design practitioners and research communities to develop new structural materials and solutions that comply with the proposed emission target values.

7. Conclusions

It is widely acknowledged that current practices being applicable across the engineering and construction sectors are responsible for a high percentage of the environmental impacts made on a global scale. To honour the goal proposed by the German Federal Government regarding carbon emission neutrality by 2045 and support practicing engineers making emission-efficient decisions, the German Committee for Structural Concrete (DAfStb) has specified a set of greenhouse gas emission reduction targets to be gradually implemented from 2020 until 2045. In this paper, two floor slab systems were evaluated in terms of greenhouse gas emissions and the results were compared to the specified emission reduction targets. This investigation enabled the following conclusions:

- The results indicate that the adoption of cast-in-situ floor slab systems will become gradually more challenging over the years when these are designed under the provisions of approach 1 (i.e., fulfilling the “basic” structural code provisions and using ordinary concrete and cement mixtures). For example, considering a live load configuration of 3.2 kN/m^2, from 2030 onwards, only spans up to 5 m appear to comply with the specified targets. For a live load configuration of 5 kN/m^2, the maximum target-compliant span is reduced to 4 m.
- Further emission-reduction opportunities are offered with the use of a maximum permissible camber (design approach 2). In terms of target-compliant spans, from 2030 onwards, the use of cambers enables the design of spans up to 5.5 m for both live load configurations (i.e., 3.2 kN/m^2 and 5 kN/m^2). The use of this design approach yields emission gains up to 15 per cent compared to the use of approach 1.
- Cast-in-situ slab systems made with modern cements (design approach 3) also offer emission-reduction opportunities. In terms of target-compliant spans, from 2030 onwards, cast-in-situ slabs with spans longer than 7.5 m that are designed for a live load configuration of 3.2 kN/m^2 or longer than 6.5 m for a live load configuration of 5 kN/m^2 seem to not verify the specified targets. In terms of greenhouse gas emissions, the use of modern cement can generate relative savings higher than 25 percent in comparison to the use of conventional mixtures in cast-in-situ slabs.
- For cast-in-situ slabs, the largest span width opportunities are given through the use of design approach 4, which combines the possibilities of a camber with the use of modern cements. With approach 4, from 2030 onwards, it appears to be possible to design spans up to 9 m for a live load configuration of 3.2 kN/m^2 and up to 8.5 m for a live load configuration of 5 kN/m^2. These values are longer than the regular spans adopted for cast-in-situ slabs, which are typically built up to values around 6.5 m and 8 m. The use of cambers with modern cements for the design of cast-in-situ slabs can yield relative savings higher than 30 per cent in comparison to the use of design approach 1, where conventional cement mixtures are considered.
- For most of the spans addressed in this investigation, precast prestressed hollow core slabs offer greater potential in terms of compliance with the specified reduction targets. When considering the design approach 1, only by 2028, spans longer than 11 m might encounter difficulties to comply with the targets. By 2030, constrains associated with the use of hollow core slabs appear for spans longer than 11 m when these are designed for any of the live load configurations.
- In the design of hollow core slab systems, the use of modern cements through the design approach 3 offers a wider range of span possibilities complying with the reduction targets: Only by 2030, spans can be designed up to 11 m for both live load configurations (3.2 kN/m^2 and 5 kN/m^2). The relative emission savings of hollow core slabs in relation to cast-in-situ slabs designed with the same design approach 3 can go up to 16 per cent.
- The results also indicate that, by 2030, the greenhouse gas emissions of relatively small spans have marginal differences in both floor slab systems. For example, when these systems are designed with the regular approach 1, spans of 4 m produce a maximum of 40 kg CO_2-Eq./m^2. For spans of 5 m, the emissions of cast-in-situ slabs vary marginally between 44 and 48 kg CO_2-Eq./m^2, whereas for hollow core slabs the emissions revolve between 40 and 43 kg CO_2-Eq./m^2. A similar trend results from the use of modern cements (design approach 3), where the emissions generated by both systems in small spans only vary minimally.

- The results confirm that hollow core slab systems are suitable alternatives to more conventional structural solutions. The gains provided by the use of these systems are even more pronounced when modern cement mixtures are considered. When the emissions of hollow core slabs designed with modern cement are compared to the emissions of cast-in-situ slabs designed with conventional approaches, savings can go up to 37 per cent.
- Two main aspects can be derived from this investigation that are relevant for structural design practitioners and research communities:
  - Reframing conventional practices might be needed since designing for structural code compliance might no longer be sufficient to meet the emission-reduction targets established in the DAfStb guideline – and ultimately, the targets established by the German Federal Government. This might include the use of more environmentally-friendly solutions (e.g., concrete-timber components, textile-reinforced concrete components) or the adoption of prestressed solutions, which might have to compete with more common structural solutions to become a preferred option among practicing engineers. Also, the adoption of more modern cement mixtures will have to be considered and further efforts on design optimisation might have to be made. Yet, these adaptations might have considerable cost implications that owners and investors should be prepared to handle.
  - Yet, the introduction of the proposed emission reduction targets offers an opportunity to communities of practice and researchers to invest in the development of novel materials and solutions that go above and beyond the proposed values.

Extending the current study to distinct slab systems (e.g., filigree slab systems, flat slabs with and without prestress or timber-concrete composite floor slabs) or different load-bearing systems (e.g., foundations or structural walls) is recommended to guarantee that the specified emission reduction targets can be applied to a wider universe of slab systems solutions. Additionally, the economical impact of the results presented in this study shall be calculated. Further work should be carried out with the consideration of the operational phase, where the influence of different heating and cooling systems can be contemplated in combination with the embodied energy presented in distinct structural systems. To this, assessments with different life cycle assessments software shall be conducted. Finally, the implications of the above-described design constraints on thermal and sound insulation performance of structural components should be also investigated.

CRediT authorship contribution statement

Tânia Feiri: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Sebastian Kuhn:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – review & editing. **Udo Wiens:** Conceptualization, Methodology, Validation. **Marcus Ricker:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The Authors greatly acknowledge the support of German Committee for Structural Concrete (In German: *Deutscher Ausschuss für Stahlbeton e.V.*, (DAfStb)) for funding this investigation.

References

[1] International Energy Agency and the United Nations Environment Programme, Global status report for buildings and construction, 2022.
[2] H. Gervasio, S. Dimova, A. Pinto, Benchmarking the life-cycle environmental performance of buildings, Sustainability 10 (5) (2018) 1454, URL: https://doi.org/10.3390/su10051454.
[3] R. Hingorani, J. Köhler, Towards optimised decisions for resource and carbon-efficient structural design, Civ. Eng. Environ. Syst. (2023) 1–31, URL: https://doi.org/10.1080/10286608.2023.2198767.
[4] S. KC, D. Gautam, Progress in sustainable structural engineering: a review, Innov. Infrastruct. Solut. 6 (2) (2021) 68, URL: https://doi.org/10.1007/s41062-020-00419-3.
[5] M. Pongiglione, C. Calderini, Sustainable structural design: Comprehensive literature review, J. Struct. Eng. 142 (12) (2016) 04016139, URL: https://doi.org/10.1061/(ASCE)ST.1943-541X.0001621.
[6] Die Bundesregierung, Intergenerational contract for the climate: Climate Change Act 2021, 2021, https://www.bundesregierung.de/breg-de/schwerpunkte/klimaschutz/climate-change-act-2021-1936846.
[7] C. Müller, M. Mohr, Wie gelingt die Dekarbonisierung des Betonbaus in der Praxis, HeidelbergCement Newsl. Tech. (2021).
[8] Deutscher Ausschuss für Stahlbeton (DAfStb), Grundsätze des nachhaltigen Bauens mit Beton, Gelbdruck 7 (2014) 2014.
[9] U. Wiens, Nachhaltig bauen mit Beton – Planungshilfe des Deutschen Ausschusses für Stahlbeton, Beton-und Stahlbetonbau 117 (1) (2022) 58–65.

[10] C. Graubner, T. Bleyer, M. Brunk, T. Dreßen, C. Fensterer, C. Gehlen, A. Haas, N. Hanenberg, B. Hauer, J. Hegger, et al., Der Stadtbaustein im DAfStb/BMBF-Verbundforschungsvorhaben: Nachhaltig bauen mit Beton, 2014.

[11] T. Feiri, S. Kuhn, M. Ricker, Immediate CO$_2$savings through optimised design approaches: A case study of reinforced concrete flat slabs, in: International Symposium of the International Federation for Structural Concrete, Springer, 2023, pp. 321–328.

[12] I. Paik, S. Na, Evaluation of carbon dioxide emissions amongst alternative slab systems during the construction phase in a building project, Appl. Sci. 9 (20) (2019) 4333, URL: https://doi.org/10.3390/app9204333.

[13] I. Paik, S. Na, Comparison of environmental impact of three different slab systems for life cycle assessment of a commercial building in South Korea, Appl. Sci. 10 (20) (2020) 7278, URL: https://doi.org/10.3390/app10207278.

[14] T.M.K.H. Trinh, S. Chowdhury, J.-H. Doh, C. Shunyao, The impacts of different structural design alternatives on the embodied emissions of flat plate buildings, in: ICSCEA 2019: Proceedings of the International Conference on Sustainable Civil Engineering and Architecture, Springer, 2020, pp. 1199–1208.

[15] A. Kong, H. Kang, S. He, N. Li, W. Wang, Study on the carbon emissions in the whole construction process of prefabricated floor slab, Appl. Sci. 10 (7) (2020) 2326, URL: https://doi.org/10.3390/app10072326.

[16] S. Na, S.-J. Heo, S. Han, Construction waste reduction through application of different structural systems for the slab in a commercial building: A South Korean case, Appl. Sci. 11 (13) (2021) 5870, URL: https://doi.org/10.3390/app11135870.

[17] Deutscher Ausschuss für Stahlbeton (DAfStb), DAfStb-Richtlinie – Treibhausgasreduzierte Tragwerke aus Beton, Stahlbeton oder Spannbeton – Teil 0: Grundlagen; Teil 1: Deckenbauteile, Version August 2023, 2023.

[18] DIN EN 15804, Nachhaltigkeit von Bauwerken – Umweltproduktdeklarationen – Grundregeln für die Produktkategorie Bauprodukte, 2012.

[19] Deutscher Ausschuss für Stahlbeton (DAfStb), DAfStb-Richtlinie – Treibhausgasreduzierte Tragwerke aus Beton, Stahlbeton oder Spannbeton – Teil 1: Grundlagen und Nachweis am gesamten Tragwerk, Version 17 June 2024, 2024.

[20] Deutscher Ausschuss für Stahlbeton (DAfStb), DAfStb-Richtlinie – Treibhausgasreduzierte Tragwerke aus Beton, Stahlbeton oder Spannbeton – Teil 2: Deckenbauteile, Version 07 May 2024, 2024.

[21] K. Zilch, C.J. Diederichs, R. Katzenbach, et al., Handbuch für Bauingenieure: Technik, Organisation und Wirtschaftlichkeit-Fachwissen in einer Hand, Springer, 2002.

[22] H. Gervasio, S. Dimova, Environmental Benchmarks for Buildings, Publications Office of the European Union, Luxembourg, 2018, URL: https://doi.org/10.2760/073513.

[23] A. de la Fuente, M.d.M. Casanovas-Rubio, O. Pons, J. Armengou, Sustainability of column-supported RC slabs: Fiber reinforcement as an alternative, J. Constr. Eng. Manage. 145 (7) (2019) 04019042, URL: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001667.

[24] I. Heo, K. Darkhanbat, S.-J. Han, S.-H. Choi, H. Jeong, K.S. Kim, Experimental and numerical investigations on fire-resistance performance of precast concrete hollow-core slabs, Appl. Sci. 11 (23) (2021) 11500, URL: https://doi.org/10.3390/app112311500.

[25] A. Pech, A. Kolbitsch, F. Zach, Decken, Vol. 5, Birkhäuser, 2015.

[26] K. Hertz, L. Giuliani, L.S.t. Sørensen, Fire resistance of extruded hollow-core slabs, J. Struct. Fire Eng. 8 (3) (2017) 324–336, URL: https://doi.org/10.1108/JSFE-07-2016-0009.

[27] T. Roggendorf, Zum Tragverhalten von Spannbeton-Fertigdecken bei biegeweicher Lagerung (Ph.D. thesis), Rheinisch-Westfälische Technische Hochschule Aachen, Germany, 2010.

[28] J. Chang, A.H. Buchanan, R.P. Dhakal, P.J. Moss, Hollow-core concrete slabs exposed to fire, Fire Mater.: Int. J. 32 (6) (2008) 321–331, URL: https://doi.org/10.1002/fam.970.

[29] V. Albero, H. Saura, A. Hospitaler, J. Montalvà, M.L. Romero, Optimal design of prestressed concrete hollow core slabs taking into account its fire resistance, Adv. Eng. Softw. 122 (2018) 81–92, URL: https://doi.org/10.1016/j.advengsoft.2018.05.001.

[30] Federation Internationale du Béton, Guide to good practice: special design considerations for precast prestressed hollow core floors, 2000.

[31] DIN EN 1168, Precast concrete products – hollow core slabs, 2005.

[32] DIN EN 1992-1-1:2011 + AC:2010, Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau. Deutsche Fassung EN 1992-1-1:2004 + AC:2010, 2011.

[33] DIN EN 1992-1-1/NA:2013, Nationaler Anhang – National festgelegte Parameter – Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau, 2013.

[34] DIN EN 1992-1-1:2015, Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau, Ergänzung A1. Deutsche Fassung EN 1992-1-1:2004/A1:2014, 2015.

[35] DIN EN 1992-1-1/NA/A1:2013, Nationaler Anhang – National festgelegte Parameter – Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau. Änderung A1, 2015.

[36] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2013.

[37] W. Mosley, R. Hulse, J. Bungey, et al., Reinforced Concrete Design to Eurocode 2 (EC2), Macmillan Education UK, Imprint: Palgrave, London, 2012.

[38] Ketonia GmbH Spannbeton-Fertigteilwerk, Spannbeton-Fertigdecke Typ VMM-VSD. Prüfbericht Nr. 4117.30-2774/2010-02. Verlängerung und Änderung der statischen Typenprüfung Nr. 4117.20-012/02/06 vom 18.04.2007, 2010, https://www.ketonia.de/fileadmin/user_upload/Fertigdecken/Spannbeton-Fertigdecken/Downloads/Typenstatik/Typ_VSD.pdf. (Last Accessed 04 October 2023).

[39] DIN 488-1:2009, Betonstahl: – Teil 1: Stahlsorten, Eigenschaften, Kennzeichnung, 2009.

[40] Deutsches Institut für Bautechnik (DIBt), Z-12.2-11: Kaltgezogener Spannstahldraht St 1470/1670 -rund, profiliert- mit Nenndurchmesser: 7,0-7,5-8,0 mm mit Anwendungsbestimmungen für Spannbetonbauteile und Felsanker, 2021.

[41] Deutsches Institut für Bautechnik (DIBt), Z-12.3-6: Spannstahllitzen St 1570/1770 aus sieben kaltgezogenen, glatten Einzeldrähten mit Nenndurchmesser: 6,9 - 9,3 - 11,0 - 12,5 - 12,9 - 15,3 und 15,7 mm sowie Korrosionsschutzsysteme für die Nenndurchmesser: 12,5 - 12,9 - 15,3 und 15,7 mm mit Anwendungsbestimmungen für Spannbetonbauteile und Felsanker, 2021.

[42] IBU - Institut Bauen und Umwelt e.V., Beton der Druckfestigkeitsklasse C30/37. Deklarationsnummer EPD-IZB-20180102-IBG2-DE, 2018, Umwelt-Produktdeklaration nach ISO14025 und EN15804+A1.

[43] IBU - Institut Bauen und Umwelt e.V., Beton der Druckfestigkeitsklasse C25/30. Deklarationsnummer EPD-IZB-20180101-IBG2-DE, 2018, Umwelt-Produktdeklaration nach ISO14025 und EN15804+A1.

[44] IBU - Institut Bauen und Umwelt e.V., Beton der Druckfestigkeitsklasse C45/55. Deklarationsnummer EPD-IZB-20180099-IBG2-DE, 2018, Umwelt-Produktdeklaration nach ISO14025 und EN15804+A1.

[45] IBU - Institut Bauen und Umwelt e.V., Zement. Deklarationsnummer EPD-VDZ-20210336-IAG1-DE, 2022, Umwelt-Produktdeklaration nach ISO14025 und EN15804+A1.

[46] IBU - Institut Bauen und Umwelt e.V., CEM II/C-M (Zusammensetzung der Hauptbestandteile: 50 % Klinker, 30 % Hüttensand, 20 % Kalkstein). Deklarationsnummer EPD-VDZ-20230234-IAG1-DE, 2022, Umwelt-Produktdeklaration nach ISO14025 und EN15804+A1, EPD-VDZ-20230234-IAG1-DE.

[47] Deutscher Ausschuss für Stahlbeton (DAfStb), Nachhaltig bauen mit Beton – Planungshilfe des Deutschen Ausschusses für Stahlbeton (DAfStb), 2021.

[48] M. Zackrisson, C. Rocha, K. Christiansen, A. Jarnehammar, Stepwise environmental product declarations: ten SME case studies, J. Clean. Prod. 16 (17) (2008) 1872–1886, URL: https://doi.org/10.1016/j.jclepro.2008.01.001.

[49] F.B. Moré, B.M. Galindro, S.R. Soares, Assessing the completeness and comparability of environmental product declarations, J. Clean. Prod. 375 (2022) 133999, URL: https://doi.org/10.1016/j.jclepro.2022.133999.

[50] DIN EN 14025, Umweltkennzeichnungen und-Deklarationen-Typ III Umweltdeklarationen-Grundsätze und Verfahren, 2011.

[51] Y.H. Ahn, A.R. Pearce, Y. Wang, G. Wang, Drivers and barriers of sustainable design and construction: The perception of green building experience, Int. J. Sustain. Build. Technol. Urban Dev. 4 (1) (2013) 35–45, URL: https://doi.org/10.1080/2093761X.2012.759887.