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Effect of Concrete Mix Composition on Greenhouse Gas Emissions over the Full Life Cycle of a Structure

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Abstract: As the need to determine and monitor carbon footprints (CFs) in the construction industry grows and given that concrete is a key construction material in this sector, the authors of the article conducted a carbon footprint analysis of 15 different concrete mixtures. The method for determining the carbon footprint of the entire life cycle of concrete was presented in detail. The authors conducted a comparative analysis of the CF for an example structure made of three significantly different concrete strength classes, in addition to determining the CF for 1 m^3 of concrete mix. This analysis showed the need to consider the entire structure and the emissivity associated with the consumption of reinforcing steel when selecting the most favorable solution in terms of greenhouse gas (GHG) emissions. The study revealed that the composition of the concrete mix, primarily the type and amount of cement, has the greatest influence on the carbon footprint. Furthermore, the location and geometry of the structure, as well as the number of floors, should also be taken into account when selecting concrete. In the analyzed construction, the life-cycle phases related to the incorporation of the concrete mixture at the construction site (phases A4–A5) and those related to the demolition of the concrete at the end of its life cycle (phases C1–C4) constituted approximately 10% on average of the total value of CF emissions over the entire concrete life cycle.

Keywords: carbon footprint; LCA of building materials; demolition process; circular economy; decarbonization

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1. Introduction

The production and exploitation of building structures are energy-intensive and material-intensive and are thus expense-intensive. Additionally, it generates a lot of waste and harmful emissions. Modern construction is increasingly being demanded to incorporate specific characteristics in the building materials used (e.g., thermal insulation, durability, strength) [1–3] and to reduce energy consumption during the construction and operation of building structures [4,5]. The most important aspect is minimalization of the environmental impact to the greatest extent possible [6,7]. According to data from 2020, the construction industry and buildings are responsible for 36% of the total global energy demand [8] and 38% of all global CO_2 emissions. Among the CO_2 emissions produced by the construction industry and buildings, 10% are released during the production and transportation of building materials, the construction process, and demolition.

The European Union is the third emitter of greenhouse gases (GHGs) in the world, just behind China and the United States [9]. Due to this fact, monitoring the level and variations of GHG emissions by individual EU countries is crucial for assessing the effectiveness of the solutions used to reduce these emissions—decarbonization [10]. It is important to pay particular attention to building materials and technologies with a low carbon footprint when designing new buildings [11]. Calculating the carbon footprint can also serve as an incentive for all parties interested in reducing greenhouse gas emissions. By providing an opportunity to track the outcomes of their efforts, it encourages them to take action towards their goals [12].

According to ISO 14067 [13], the carbon footprint is the sum of all GHGs emissions and absorptions during the full life cycle of a product (from cradle to the grave). When justified, the carbon footprint is determined from the extraction of raw materials to the delivery of the finished product to the customer (from cradle to gate). The principles of formulation on which Type III Environmental Product Declarations of building materials (EPDs) are based are recommended as a guideline for calculating CF and are often used to obtain information on the emission factors of specific products [14]. The study [15] specifies two methods for estimating the carbon footprint of buildings: the simplified method, which includes modules A1–A3 and B6, and the full method, which considers each of stages A1–A5, B1–B4, B6, and C1–C4. The simplified method is currently the most widely used method due to the low availability of databases containing individual emission factors.

From the perspective of a building structure, the carbon footprint can be divided into embedded and operational as showed in Figure 1.

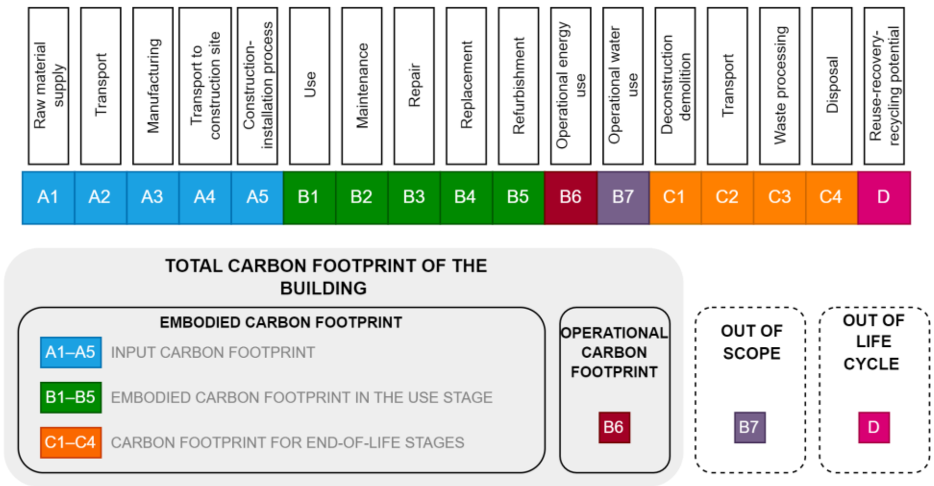


Figure 1. Types of carbon footprint from the perspective of a building structure. Own elaboration based on.

In addition to carbon dioxide emissions, the carbon footprint also includes other greenhouse gases, including methane CH_4 and nitrous oxide N_2O (a full list of greenhouse gases is available in the IPCC report [16]). The magnitude of CF is expressed in terms of carbon dioxide equivalents per functional unit of product (CO_2e/functional unit). By bringing all global warming impacts to a common scale, this makes it possible to easily compare the results and assess the overall impact [10,13]. To calculate the CO_2e value, the masses of gases are multiplied by their global warming potential (GWP), which is typically determined over a period of 100 years and listed in Table 1. Afterward, the values are added together to obtain the total CO_2e value [10,13].

Table 1. GWPs of the most commonly considered greenhouse gases in the footprint analysis. Own elaboration based on [16].

Chemical Formula	GWP_{100}
CO_2	1
CH_4—fossil origin	29.8
CH_4—non fossil origin	27.2
N_2O	273

In recent years, the topic of carbon footprint has gained significant attention due to a variety of factors. Not only is there growing concern about the environmental impact of carbon emissions, but legislative changes and increased public awareness have also contributed to the rising interest in this issue [17]. It is commonly used in the marketing activities of companies in industries, to demonstrate competitive advantage [18]. Among the most important legal documents on CF are the European Green Deal [19] and the FIT for 55 package [20].

The aforementioned legal and environmental aspects, as well as social trends, are driving the growing interest as well as the need to calculate the carbon footprint, resulting in new and improved methods for this purpose. Despite the many ongoing studies, the level of research is still at an early stage and lacks not only a uniform standard database but also assessment models [21–23].

The literature provides guidance on how to reduce carbon emissions in the construction industry, including detailed plans for achieving decarbonization [24–26]. The authors of the standard [15] also indicate that efforts to decarbonize have been focused mainly on the operational footprint, with insufficient attention paid to the built-in footprint and the final stages of the life cycle. Reducing only the operational phase of the building is insufficient; a holistic approach to CF assessment is required. Studies show that improving the energy efficiency of the building resulted in an 82% reduction in CF emissions for this life cycle phase, while increasing the CF of the construction phase by 14% [27]. Engaging in activities aimed at waste reduction and the recycling of construction and demolition materials can be instrumental in lowering carbon emissions [28]. It is therefore necessary to develop a future decarbonization assessment framework for both construction and demolition processes, which will make it possible to track the impact of efforts [29,30]. In line with this idea, decision-making models are already being developed to select the optimal solution from the perspective of reducing the carbon footprint of a given project throughout its life cycle [31], which is another argument for the need to standardize calculation methods so that this practice can become standard.

The environmental impact of concrete and other cement-based materials is becoming increasingly significant given their mass use [32]. This has led to widespread focus and a search for solutions to reduce GHGs throughout the life cycle of concrete by researchers and manufacturers. Concrete is the most widely used building material in the world [33]. As technology advances, it is expected to meet increasingly stringent requirements. One of the key expectations is to maintain sufficient quality, which must be closely monitored throughout various stages of the material's life cycle, such as during ingredient selection and design, production, delivery, and pre- and post-placement [34–37]. The European Cement Association Cembureau has established a plan for achieving carbon neutrality in the cement and concrete value chain by 2050 [38]. The operations carried out by the cement and concrete industry are highly significant for sustainable development and consumption policies, as they involve the use of natural resources and notably affect the energy balance of each country [39]. In addition, concrete recycling is critical to achieving a material efficient society, which also has an impact on greenhouse gas emissions [40]. The authors of the paper conducted a carbon footprint analysis on 15 different concretes due to the arguments presented that emphasized the importance of defining and monitoring carbon footprint in the construction industry and the fact that concrete is a vital building material for the industry. Since the majority of available publications focus on only certain aspects, such as components of the concrete mix (e.g., [41]) or the initial phase of the life cycle (e.g., [42]), the analysis developed dealt with the entire concrete life cycle (from cradle to grave) and, as previously, demonstrates the need for a holistic approach. The evaluation was designed to examine the impact of the various stages of the concrete life cycle on its carbon footprint and to compare concretes with different compositions and compressive strengths in this regard. Moreover, the method of calculating the carbon footprint is presented in detail, which can be used in decision models for the selection of the optimal solution in terms of greenhouse gas emissions, given the widespread interest in this topic as well as the continuing deficiencies and development of the methodology. Besides determining the CF for 1 m^3 of concrete mix, the authors conducted a comparative analysis of the CF for a structure made of three significantly different classes of concrete. This allowed to indicate the effect of the concrete class on the amount of mix and reinforcing steel used and thus the total amount of GHGs emissions of the analyzed structure.

2. Materials and Methods

2.1. Specifications of Concretes and Structures under Analysis

The analysis was conducted for the full life cycle of a reinforced concrete structure (from cradle to grave), as shown in Figure 2, with particular attention to the characteristics of the concrete used. The functional unit was defined as 1 m^3 of concrete. The carbon footprint was evaluated for 15 types of concrete mixtures, the composition of which was assumed on the basis of the literature data:

- Ordinary concrete of normal strength class—NSC according to [43];
- Self-compacting concrete based on slug cement (CEM III)—SCC 1, fly-ash cement (CEM II)—SCC 2, and Portland cement (CEM I)—SCC 3 according to [43];
- High-performance concrete—HPC according to [43];
- High-performance self-compacting concrete—HPSCC according to [43];
- Concrete with 50% of recycled aggregate—RAC 1 and 100% of recycled aggregate—RAC 2 according to [44];
- Geopolymer concrete—GPC according to [45];
- Lightweight concrete—LC according to [46];
- Fiber-reinforced concrete with steel fibers—FBS 1-3 [47];
- Fiber-reinforced concrete with glass fibers—FSG according to [48];
- Reactive powder concrete—RPC [49].

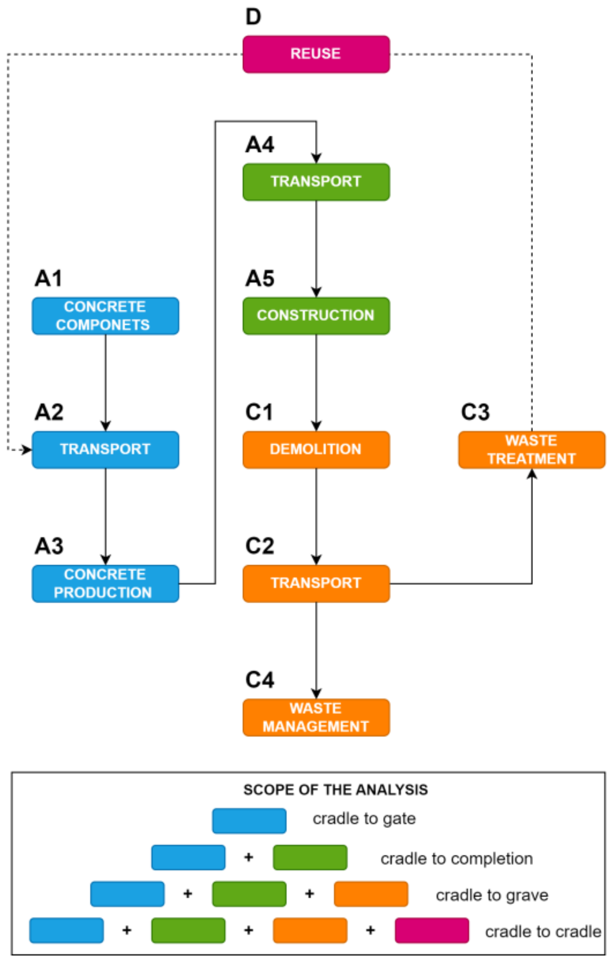


Figure 2. Life cycle of concrete. Own elaboration based on [14,15].

Figure 3 shows the adopted variant for the end of life of concrete.

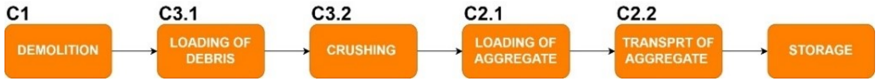


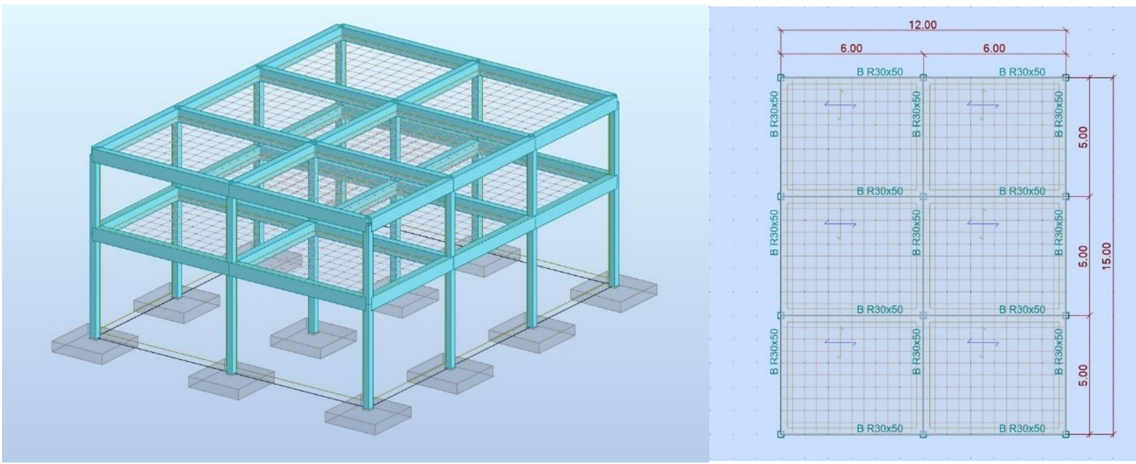
Figure 3. End-of-life process included in the analysis.

Table 2 shows the compositions of the various concrete mixtures, their compressive strengths, and the CF values of the components. The data are derived from either the GWP impact category contained in the EPDs, or it was adopted from published research. Due to the lack of information for basalt, the value was estimated based on the data of granite extraction which has a similar technology. On the other hand, the value of Ground Granulated Blast-Furnace Slag (GGBS) was assessed in the results of economic allocation [50]. The GWP value for structural steel was adopted from [51].

Concretes were divided into three groups based on its mean compressive strength f_{cm}:

- I—$f_{cm} \leq 30$ MPa;
- II—30 MPa < $f_{cm} \leq 80$ MPa;
- III—80 MPa < f_{cm}.

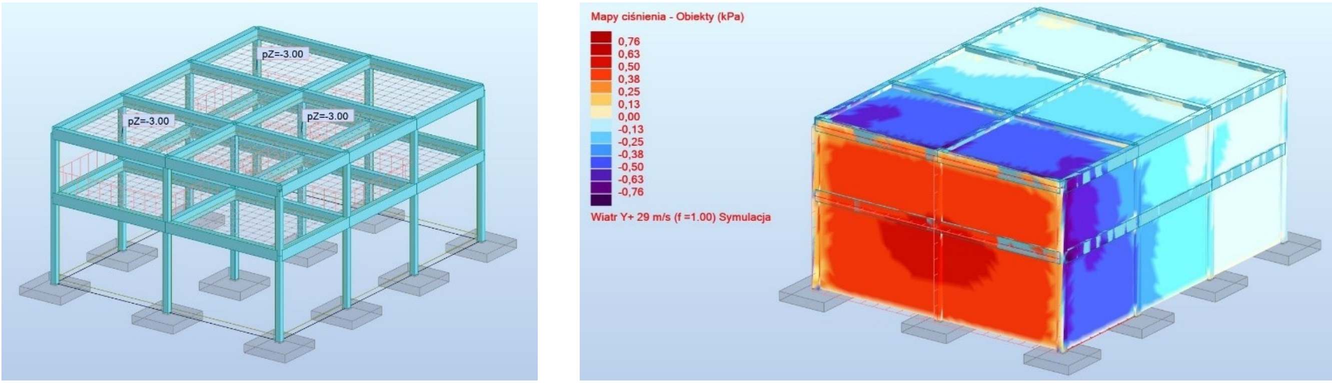
Given this categorization, an examination was conducted to determine how the particular concrete mixture used impacted the overall carbon footprint of a representative reinforced concrete structure. The assessment concerned a two-story building with a commercial use, in which structural elements were designed for 3 significantly different classes of concrete. The building, which measures—in plan—12 × 15 m and has an overall height of 7.0 m, was designed in post-and-beam construction with 2-way reinforced slabs and an external walkway (Figure 4).



(**a**) (**b**)

Figure 4. Reinforced concrete structure model under analysis: (**a**) general view; (**b**) view of the reinforced concrete structure (geometric dimensions in m).

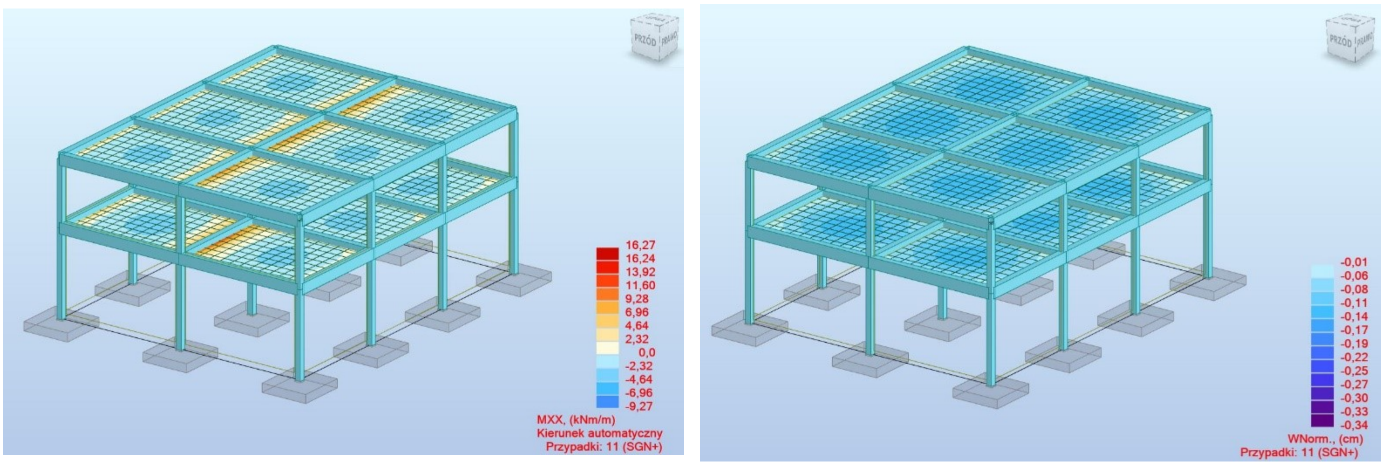
The calculation model assumed the interaction of forces on the structure from the dead weight of individual structural elements, service loads, and climatic loads (Figure 5). Load combinations were made based on the standard codes [52,53]. The tools of Autodesk Robot Structural Analysis Professional 2013 software [54] that generate automatic combinations based on the partial factor method were used.



(**a**) (**b**)

Figure 5. An exemplary load acting on the analyzed reinforced concrete structure: (**a**) example service load; (**b**) example wind load (push on gable wall).

Static calculations were performed for the adopted model, which made it possible to determine the values of cross-sectional forces in individual structural elements (Figure 6). Designing in terms of ultimate limit state and serviceability limit state was conducted in variants according to [55], assuming that the load-bearing structure of the building (footings, columns, beams, and slabs) was made from concrete class of C20/25, C50/60, and C90/105. Designing of individual structural elements was carried out assuming constant dimensions of their lengths and by optimization due to the consumption of concrete and steel of the remaining geometric dimensions.



(**a**) (**b**)

Figure 6. Examples of load combination effects: (**a**) map of flexural moments in the XX direction for floor slabs in ULS; (**b**) map of deflections of floor slabs in ULS.

Table 2. Concrete mix compositions used in the analysis.

	Ingredients	CF kgCO_2e/kg	Source	Concrete [kg/m^3] NSC	SCC 1	SCC 2	SCC 3	HPC	HPSCC	RAC 1	RAC 2	GPC	LC	FBS 1	FBS 2	FBS 3	FSG	RPC
Cement	CEM I	0.8890	[50]	380	-	-	310	-	-	335	335	-	400	255	330	475	616	905
	CEM II	0.7040		-	-	350	-	455	500	-	-	-	-	-	-	-	-	-
	CEM III	0.4820		-	370	-	-	-	-	-	-	-	-	-	-	-	-	-
GGBS	GGBS	0.0020	[50]	-	-	-	-	-	-	-	-	40	-	-	-	-	-	-
Aggregate	Sand 0–2 mm	0.0031	[43]	580	700	713	700	668	840	-	-	655	700	-	-	-	1355	-
	Sand max. 4.75 mm	0.0031		-	-	-	-	-	-	865	865	-	-	859	790	643	-	-
	Gravel 2–8 mm	0.0031		400	468	477	375	-	-	-	-	-	-	-	-	-	-	-
	Gravel 8–16 mm	0.0031		860	468	477	375	-	-	-	-	-	-	-	-	-	-	-
	Quartz Sand	0.0200	[56]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	987
	Crushed limestone	0.0630	[50]	-	-	-	-	-	-	538	-	-	-	1069	1069	1069	-	-
	Basalt 2–8 mm	0.0064	[57]	-	-	-	-	1240	990	-	-	-	-	-	-	-	-	-
	Basalt 8–16 mm	0.0064	[57]	-	-	-	-	-	-	-	-	1216	608	-	-	-	-	-
	Granite 4–8 mm	0.0064	[57]	-	-	-	-	-	-	-	-	-	267	-	-	-	-	-
	Lightweight expanded clay	0.1270	[58]	-	-	-	-	-	-	-	-	-	67.8	-	-	-	-	-
	Concrete waste	0.0047	[59]	-	-	-	-	-	-	490	980	-	-	-	-	-	-	-
Water	Water	0.0006	[43]	190	170	161	200	160	160	182	182	8	110.4	180	180	180	254	260
Additives	Silica fume	0.0039	[43]	-	-	-	-	45	-	-	-	-	40	-	-	-	53.6	230
	Fly ash	0.0020	[50]	-	180	200	190	-	-	-	-	360	-	-	-	-	-	-
	Steel fibres	1.2800	[60]	-	-	-	-	-	-	-	-	-	-	39	39	39	-	233
	Glass fibres	1.4400	[61]	-	-	-	-	-	-	-	-	-	-	-	-	-	13.5	-
	Superplasticizer	1.5300	[62]	3.8	2.59	2.45	6.5	4.05	5.55	-	-	6	8.8	0.89	1.16	1.66	3.84	29.6
	Na_2SiO_3 (solution)	0.823	[63]	-	-	-	-	-	-	-	-	84	-	-	-	-	-	-
	NaOH	0.070	[64]	-	-	-	-	-	-	-	-	56	-	-	-	-	-	-
Mechanical compaction				YES	NO	NO	NO	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES
Average compressive strength f_{cm} [MPa]				41.2	42	47	37	91.1	90.5	31	28	27	88.3	25.5	37	55	83	106

The use of high-performance concretes in the analyzed facility enabled the reduction of the amount of concrete and reinforcing steel compared to normal strength concrete in the individual structural elements. The reduction in concrete was mainly related to the columns, which, due to the nature of their work, transmit eccentrically acting compressive forces. In slabs made of higher-class concretes, there was no significant reduction in their thickness. The reason for this is the bi-directional operation of the slabs over their entire surface and the significant effect of flexural moment on their load-bearing capacity.

The obtained values of steel and concrete mix demand for each material solution are shown in Table 3 (the values do not consider the waste surcharge).

Table 3. Consumption of concrete and reinforcing steel in the analyzed reinforced concrete structure depending on the adopted concrete class.

	Concrete Classes	Reinforcing Steel [Mg]	Concrete [m^3]
Construction 1	C20/25	7.47	104.19
Construction 2	C50/60	7.06	95.97
Construction 3	C90/105	7.00	94.04

It should that the analysis conducted did not consider the suitability of using a specific concrete mix in the analyzed structure, given factors such as concrete durability and other performance parameters.

2.2. Carbon Footprint of Concrete—Calculation Method

The carbon footprint CF (Equation (1)) for the entire life cycle of concrete was determined following [13] as the quotient of the sum of its CF_i values for individual ranges $A1$–$C4$ (Equations (2)–(5)), and the volume of concrete (V) in the entire structure (V was increased by a 5% waste allowance for process waste, e.g., from using a concrete pump, based on the [15]):

$$CF = \frac{\sum_{i=A1}^{C4}(CF_i)}{V}\left[\frac{\text{kgCO}_2\text{e}}{m^3}\right] \quad (1)$$

The value of CF_{A1} was determined using an Equation (2) as the sum of the products of the CF_j values and the mass m_j for the individual concrete components:

$$CF_{A1} = \sum_{j=1}^{n}(CF_j \cdot m_j)[\text{kgCO}_2\text{e}] \quad (2)$$

Emissions for transport were determined for the Euro V engine class of transport vehicles, assuming transport for a maximum distance of 100 km and a loading factor of 0.85 [43]. Due to the small share of steel fibers (RPC exception), superplasticizer, and activators Na_2SiO_3 and NaOH in the mix, emissions related to the transport of these materials were omitted. For calculation purposes, the ratios developed for the Tier 1 and Tier 2 methods in publication [65] were used and are presented in Table 4. The magnitude of CF for the $A2$, $A4$, $C2.2$ range was defined according to Equation (3):

$$CF_{A2,A4,C2.2} = \sum_{j=1}^{n}[l_j \cdot (E_{lCO_2} + 273 \cdot E_{tN_2O} + FC \cdot E_{fCO_2} + FC \cdot SC)][\text{kgCO}_2\text{e}] \quad (3)$$

where l_j is the transport distance (taking into account the number of necessary trips) for the individual concrete components; E_{lCO_2}, E_{tN_2O}, and E_{fCO_2} are the emission factors of CO_2 and N_2O; FC is the fuel consumption; and SC is the supply chain indicators of diesel (Table 3).

Table 4. Data used to calculate transportation emissions. Own elaboration based on [65].

Loading Capacity [t]	Transport	Exhaust Emission Factors			Fuel		
		E_{tCO_2} [kgCO$_2$e/km]	E_{tN_2O} [kgN$_2$Oe/km]	Typical Fuel Consumption [kg/km]	E_{fCO_2} [kg/kg fuel]	Diesel Supply Chain Indicator *SC* [kgCO$_2$e/kg]	Diesel Supply Chain Indicator *SC* [kgCO$_2$e/l]
7.5–16	the ingredients of the concrete mixtures	$0.486{\cdot}10^{-3}$	$0.034{\cdot}10^{-3}$	0.155	3.169	0.395	0.332
16–32	concrete mixtures, debris			0.210			

The factors in Table 5 were used to determine the emissions associated with on-site production, pumping, and compaction of the concrete mix. Due to the lack of information on N_2O emissions, the factors for NO_x were used.

Table 5. Electricity demand for A3, A5 processes.

Process	Production *	Pumping	Compacting
Scope	A3	A5	A5
Process energy consumption [kWh/m^3]	29.66 [66]	0.49 [43]	0.25 [43]

* Included in the concrete production process are placement and transportation of aggregate and cement at the plant, mixing of aggregate, cement, and water by the concrete plant, and loading of concrete into the concrete mixer.

Emissions associated with ranges $A3$ and $A5$ were calculated based on Equation (4) as the sum of the products of the electricity end-use emission factor (E_{eCO_2}, E_{eNOx} according to the National Balancing and Emissions Management Center Report [67] 0.698 kg/kWh and 0.000522 kg/kWh, respectively), the process-specific energy use factor E_{ck}, and the volume of concrete mix V.

$$CF_{A3,A5} = \sum_{k=1}^{n} (E_{eCO_2} + 273{\cdot}E_{eNO_x}){\cdot}E_{ck}{\cdot}V[\text{kgCO}_2\text{e}] \quad (4)$$

To determine $CF_{C1,\,C3.1,\,C3.2,\,C2.1}$ for demolition processes, the methodology developed by J. Sagan in her paper [68] and the non-road model [69] were used. Demolition (C1) was conducted using an excavator equipped with hydraulic hammers, followed by loading of the rubble by the excavator ($C3.1$) into a crusher ($C3.2$) and after crushing onto cars ($C2.1$). The parameters of the equipment used are listed in Table 6.

Table 6. Equipment parameters. Own elaboration based on [68].

Vehicle Category	Power [kW]	Average Technical Performance [Mg/h]	Maximum Volume of the Excavator Bucket [m^3]
Hydraulic hammer	110	According to Equations (8)–(10)	-
Excavator	110	According to Equation (11)	1.5
Crusher	29.6	17.5	-

The carbon footprint was calculated by determining the operating time of the listed equipment and, on this basis, specific emissions from combustion and fuel consumption—Equation (5):

$$CF_{C1,C2} = EF_{CO_2} + 273{\cdot}E_{NO_2} + Fuel_k{\cdot}h{\cdot}E_{tCO_2} + Fuel_k{\cdot}h{\cdot}SC[\text{kgCO}_2\text{e}] \quad (5)$$

where EF_{CO_2}, EF_{NOx} are unit emissions for CO_2 by and for N_2O, respectively (Equation (12)); h is equipment operating time (Equation (6)); and $Fuel_k$ is fuel consumption (Equation (18)),

$$h = V \cdot \frac{1}{W_{eh,ec}} [h]$$
$$h = V \cdot \rho_n \cdot \frac{1}{W_{ee}} [h] \tag{6}$$

where $W_{eh,ec}$ (Equation (7)) is the operating capacity for the hydraulic hammer and crusher; and for the excavator W_{ee} (Equation (11)), ρ_n bulk density for rubble 1.7 [Mg/m^3] [68], and for recycled aggregate 2.47 [Mg/m^3] [70]

$$W_{eh,ec} = W_t \cdot S_w \left[\frac{\mathrm{m}^3}{h}\right], \tag{7}$$

where W_t is the technical capacity for hydraulic hammers W_t = W_{th} (Equations (8)–(10)); for the crusher W_t = W_{tc} according to Table 7; and S_w is the working time utilization factor equal to 0.8.

Table 7. Indicators used in the calculations for the phase of C1, C3.1, C3.2 *i* C2.1. Own elaboration based on [68].

	i [-]	*EF_{ss}* [g/kWh]		*TAF* [-]	h_{culm} [h]	M_{flh} [h]	A_{HC} [-]	A_{NOx} [-]	$BSFC_{ss}$ [lb/kWh]
		HC	NO_x						
Excavator (Tier 4N)	0.59	0.176	0.370	1	1092	4667	0.027	0.008	0.492
Crusher (Tier 4)	0.43		4.023		955	2500			0.547

The technical capacity expressed in m^3/h for hydraulic hammers was determined by the thickness of the element to be demolished (15 cm), and the compressive strength of the concrete from which the element was formed—Equations (8)–(10):

$$80\ \text{MPa} < \mathrm{f_{cm}} \qquad W_{th}(x) = 8 \cdot 10^{-5} \cdot x^3 - 0.0135 \cdot x^2 + 0.589 \cdot x + 1.3862 \tag{8}$$

$$30\ \text{MPa} < \mathrm{f_{cm}} \le 80\ \text{MPa} \quad W_{th}(x) = 2 \cdot 10^{-5} \cdot x^3 - 0.0069 \cdot x^2 + 0.5829 \cdot x + 6.258 \tag{9}$$

$$\mathrm{f_{cm}} \le 30\ \text{MPa} \qquad W_{th}(x) = -1 \cdot 10^{-5} \cdot x^3 - 0.0032 \cdot x^2 + 0.5977 \cdot x + 7.3226 \tag{10}$$

Operating capacity for the excavator determined according to Equation (11):

$$W_{ee} = \frac{(V_{eb} \cdot \rho_n) \cdot 3600}{T} \cdot S_n \left[\frac{Mg}{h}\right], \tag{11}$$

where V_{eb} is the volume of the excavator bucket (Table 6); S_n is the filling factors of the working vessel 0.85 [71], while T is the duration of the excavator's working cycle including the time of auxiliary processes [68].

Individual emissions (Equation (12)) are dependent on engine power P, process time h, emissions of a specific type of pollutant ($EF_{(HC,\ NOx,\ CO_2)}$—Equations (13) and (14)), and engine load factor i:

$$E_{(HC,NO_x,CO_2)} = P \cdot h \cdot EF_{(HC,NO_x,CO_2)} \cdot i \left[\frac{kg}{kWh}\right] \tag{12}$$

Pollutant emissions by type are defined as Equation (13) (for HC and NO_x) and Equation (14) (for CO_2):

$$EF_{(HC,NO_x)} = E_{ss(HC,NO_x)} \cdot TAF \cdot DF \, [\frac{kg}{kWh}] \tag{13}$$

where $EF_{ss(HC,\,NOx)}$ is the emission factor in the initial state (Table 7) DF is the deterioration factor calculated using Equation (15); and TAF is the correction factor (Table 7),

$$EF_{CO_2} = (BSFC \cdot 0.4536 - EF_{HC}) \cdot 0.87 \cdot \frac{44}{12} \, [\frac{kg}{kWh}] \tag{14}$$

where $BSFC$ is the volume of fuel needed to generate a unit of power—Equation (17); 0.4536—converter of lb units to kg, 0.87 mass fraction of carbon in diesel; 44/12—molecular weight ratio of carbon dioxide and carbon.

The factors DF (Equation (15)) and AF (Equation (16)) are defined as:

$$DF = \begin{cases} 1 + A \cdot AF, dla\ AF \leq 1 \\ 1 + A, dla\ AF > 1 \end{cases} \tag{15}$$

$$AF = \frac{h_{culm} \cdot i}{M_{flh}} dla\ AF \leq 1 \tag{16}$$

where A is the relative deterioration factor; h_{culm} is the total operating time of the machine to date (Table 7), while M_{Lflh} is the average lifetime at full load operation (Table 7).

$$BSFC = BSFC_{ss} \cdot TAF \, [\frac{lb}{kWh}] \tag{17}$$

where $BSFC_{ss}$ is the volume of fuel required to generate a unit of power in the initial state of Table 7.

$$Fuel_k = \frac{(BSFC \cdot 0.4536) \cdot P \cdot i}{0.84} \, [l] \tag{18}$$

where 0.84 is the density of diesel [kg/l].

3. Results and Discussion

The amount of carbon footprint for one cubic meter of concrete mix determined by the simplified method (range A1–A3) is presented in Figure 7.

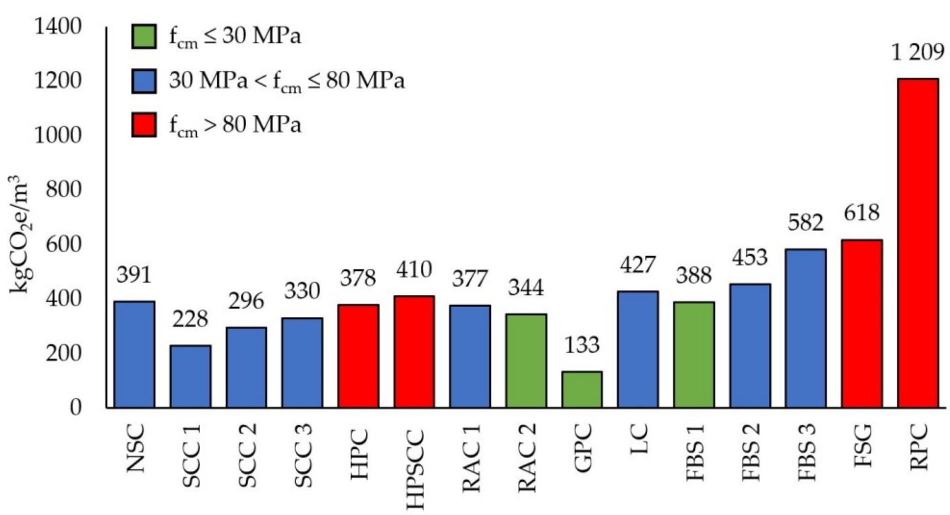


Figure 7. Carbon footprint for phase A1–A3 per 1 m^3 of concrete mix.

The extreme values of GHGs emissions obtained for RPC (the highest value) and for GPC (the lowest value) are notably different from the other results. It is related to the significant difference in the cement content for these mixtures compared to the other compositions presented. This highlights the strong correlation between CF values and the amount of cement utilized in the compositions presented.

Analyzing the mixtures of the SCC group, which had comparable compositions but differed only in type of cement utilized, it was concluded that the CF was also affected by the type of cement. This is supported by the results of a publication [41] in which mixtures with CEM I, CEM II and CEM I, CEM III were used and were compared among themselves, resulting in a difference in emissions of 73–150 $kgCO_2/m^3$. The reason for this can be attributed to the fluctuating proportion of clinker, which is being substituted by alternative binder materials with considerably lower emission rates (such as fly ash [72], GGBS [73], and even plastic waste [74]), for which almost zero GHGs emissions are assumed due to their waste origin [42]. This was confirmed by the example of the GPC concrete analyzed. A similar relationship was also observed in HPC and HPSCC concretes, for which, despite the higher amount of CEM II cement, comparable or lower CF values were obtained compared to FBS 1–3, NSC, and LC concretes that used CEM I.

Globally, no significant correlation was observed between the compressive strength and the CF value, as shown by a comparison of, for example, FBS mix to SCC 1. The reason for this is the influence of many factors on the strength of concrete, such as grain size, quantity, and quality of aggregate and water-to-cement ratio, which was also confirmed by the results of the work [6]. However, considering the strength for one type of mix (FBS), it could be noted that as the strength increased, so did the amount of GHGs emitted. This correlation was also confirmed by the authors of the paper [75], who developed an empirical relationship that allowed estimating individual CO_2 emissions as a function of compressive strength for cylindrical specimens. The increase in GHGs emissions with increasing compressive strength of concrete was caused primarily by the higher amount of cement in higher classes of concrete.

Comparison of normal strength concrete—NSC with concrete containing recycled aggregate—RAC 1 and RAC 2 indicated a decrease in CF values for mixtures in the RAC group. However, it is important to acknowledge that as the proportion of recycled aggregate increased, the compressive strength of the tested concretes decreased. The results of [76] demonstrated that for concrete with a compressive strength of less than 45 MPa, it is possible to produce concrete with recycled aggregate with the same strength and durability as concrete with traditional aggregate. Additional emissions might be avoided by optimizing the mix design. To achieve comparable characteristics to concrete on crushed aggregate in high-strength concrete using recycled aggregate, a larger amount of cement would be required, which can result in up to three times higher CO_2 emissions than regular concrete mixtures. Practice has shown that recycled aggregate can be cost competitive with natural aggregates. High profits can be obtained when ordinary aggregates are unavailable locally and must be delivered from considerable distances, which also reduces emissions resulting from transportation [39]. Considering this aspect, it is worth to mention the analysis carried out in the work [77], which showed that, considering the strength and economic parameters of concrete, it is reasonable to use recycled aggregate (RCA) when the transport distance of fine natural aggregate is at least twice as large as for this recycled aggregate. The reduction in the carbon footprint of concrete as a result of using locally available aggregates is presented in [78]. The paper [79] emphasized the need to promote Green Supply-Chain Management (GSCM) as a tool to support energy transformation and energy conservation and emission reduction in the manufacturing industry. Research in terms of natural aggregate substitutes did not focus only on recycled concrete aggregate but also on the use of waste materials from other industries, e.g., PET (waste fraction from PET bottle recycling) [80], which is in line with the idea of a closed-loop economy [81].

Table 8 shows a comparison of the results obtained in relation to other publications. The obtained results relate only to phase A1, and the differences obtained are primarily due to the adopted assumptions and computational methods, which means that they cannot always be compared with each other.

Table 8. Comparison of results with other studies.

Type of Concrete	Range	Own Results		Other Results		Source
		CF [$kgCO_2e/m^3$]	Compressive Strength [MPa]	*CF* [$kgCO_2e/m^3$]	Compressive Strength [MPa]	
Concrete based on CEM I	A1	305	28	215	25	[82]
		291–349	30–80	310–378	30–50	[41]
		291–349	30–80	350	60	[82]
		386	88	394	80	[82]
RAC 1		337	31	347	31	[44]
RAC 2		305	28	334	28	[44]
FSB 1		348	26	370	25.5	[47]
FSB 2		415	37	439	37	[47]
FSB 3		544	55	572	55	[47]

Figure 8 provides a comparison of the percentage contribution of the carbon footprint of the different component groups and A2–A3 phases to its total size for analyzed concrete mixtures. The results confirmed the previously described conclusions related to the influence of the amount and type of cement on the CO_2e value.

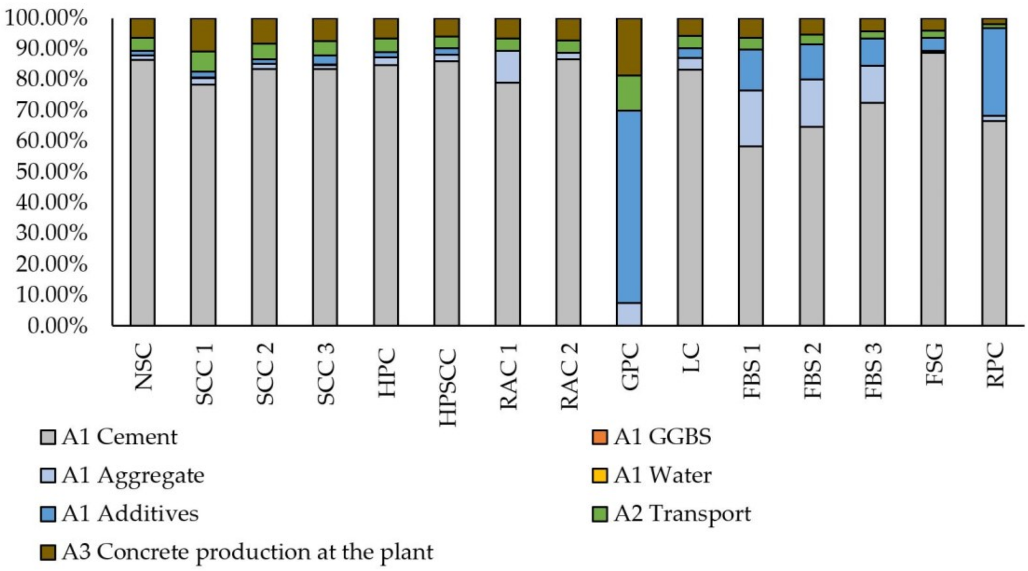


Figure 8. Percentage contribution of concrete mix components as well as A2 and A3 phases in the carbon footprint value.

For NSC, SCC1-3, HPC, HPSCC, RAC 2, and LC mixtures, the effect of components other than cement on CF could be considered negligible. For mixtures with a significant content of aggregate or fibers, the impact on the issue was evident, and possible attempts to reduce emissions for these components could perceptibly affect the value of GHGs emissions. It is worth mentioning that while searching for EPDs, part of the values was taken from studies conducted in various countries, which indicated the current limited availability and scope of databases. Additionally, it is important to recognize that values may vary across regions due to different "energy mixes" in these countries.

Figure 9 illustrates the obtained carbon footprint values for the entire life cycle of the analyzed object made of the investigated concretes per 1 m^3 of concrete mix.

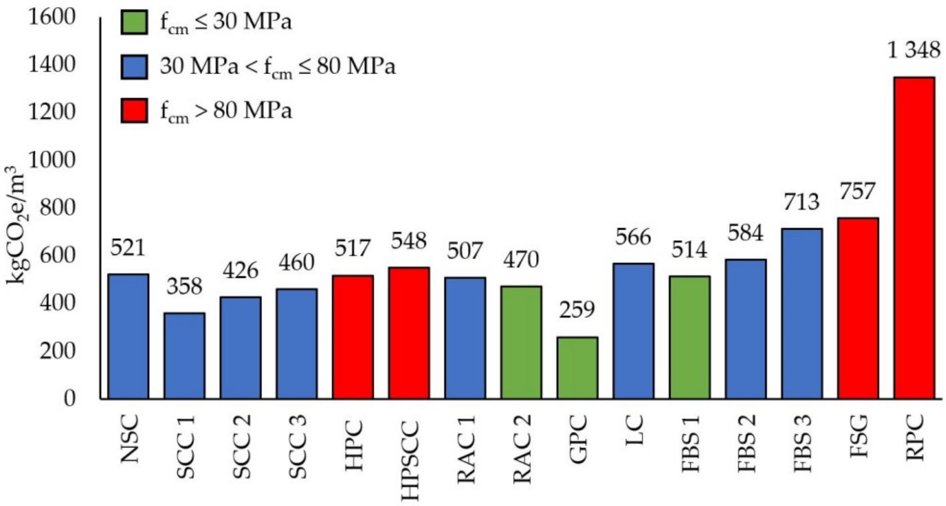


Figure 9. Carbon footprint over the life cycle of concrete per 1 m^3 of concrete mix.

It is worth noting that there was a relatively small difference in GHGs emission values for HPC concrete compared to other concretes with compressive strengths of less than 80 MPa. This relationship appeared to be crucial from the perspective of a particular construction. Higher compressive strength of concrete could lead to thinner structural elements or a reduced use of reinforcing steel, which globally may result in a smaller carbon footprint for the entire structure. Therefore, when selecting a concrete mix for a specific building project, it is crucial to consider not only the emissions per functional unit but also how it relates to the overall structure. In paper [82], a carbon footprint analysis was carried out for normal- and high-strength concrete in reference to three reinforced concrete building structures with 14, 30, and 60 stories, respectively. The size of the carbon footprint was defined as a function of both concrete strength and building height. The analysis showed that for structures with the smallest number of floors, there was a gradual increase in CO_2 emissions together with the increase in concrete class, while for a 60-story building the relationship was reversed.

The order of concretes ranked by emissivity did not change when using either the simplified method (range A1–A3) or the full method (whole life cycle), except for HPC concrete (from 7th place to 8th) and FBS 1 (from 8th to 7th). Hence, this would seem to confirm that as long as no extensive measures are taken in terms of reducing emissivity in the initial phase of the concrete life cycle, the simplified method is an acceptable method for the comparison of the various material solutions for concrete structures with the main binding component in the form of cement. In the case of GPC concretes, it may be worthwhile to perform the analysis over the entire life cycle since the contribution of the other phases becomes more significant.

Figure 10 shows the percentage contribution of the carbon footprint of the various phases of the concrete life cycle to the total. By far the largest share of the total concrete life cycle was associated with phases A1–A3. The remaining phases for most structures accounted for an average of 10%. However, the paper did not consider the location of the analyzed construction, which could have substantial impact on the availability of materials and transportation distance. Analyzing the graph in Figure 10, it becomes apparent that the influence of transportation and on-site processes during the technological and demolition phases become noteworthy only after implementing measures to reduce carbon footprint during phase A1. This observation is exemplified in the case of GPC mix.

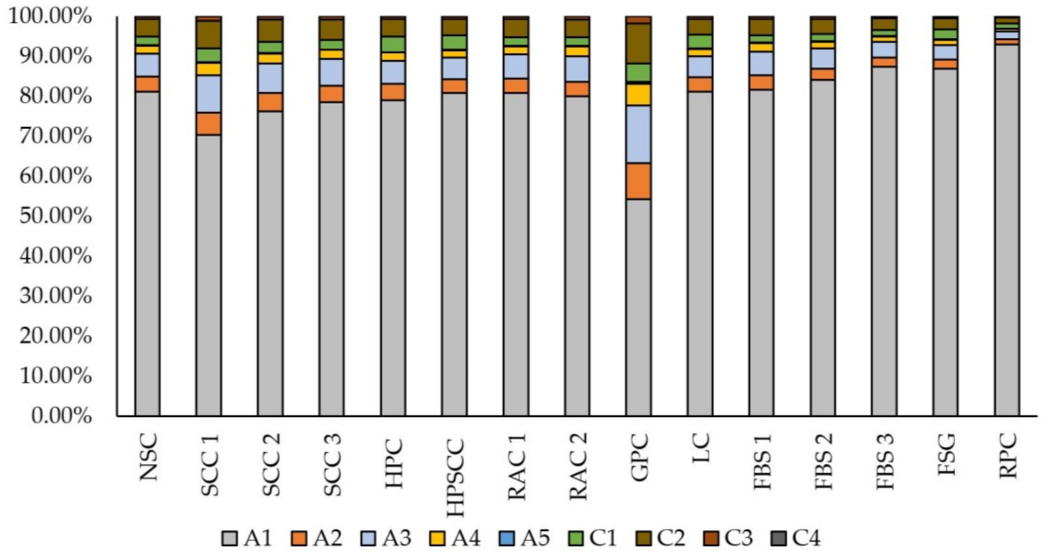


Figure 10. Percentage contribution of the different life cycle phases of the analyzed concretes to the carbon footprint value.

Figure 11 illustrates the carbon footprint values obtained for varying amounts of concrete mix and required steel in the analyzed. The contribution of these components to the total CF value of the analyzed structure contributed an average of 15%. It should be noted that the proportion of steel and concrete required can vary significantly depending on the strength class of concrete used and the number of floors of the structure, which can result in different proportions of steel and concrete required.

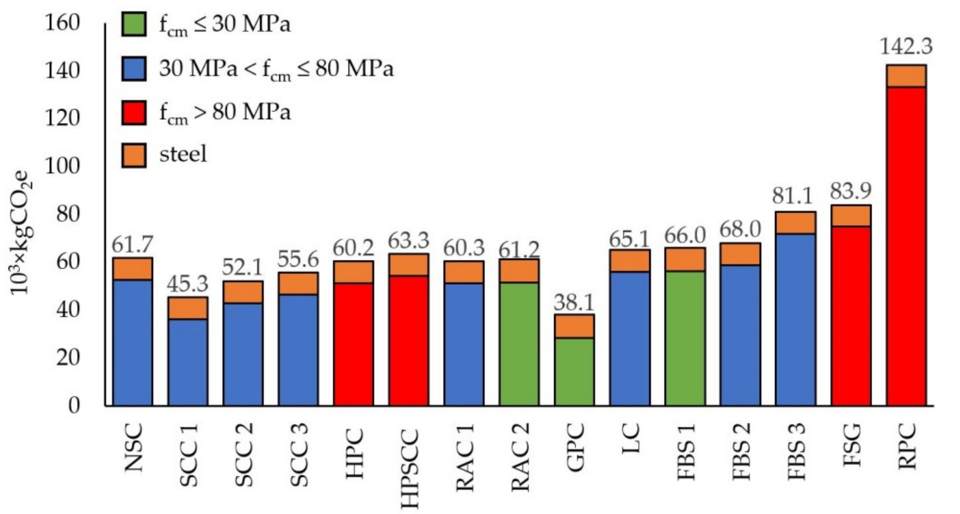


Figure 11. Carbon footprint value over the entire life cycle for concrete and reinforcing steel in the analyzed structure.

The obtained value of GHGs emission per 1 m^3 for NSC concrete (group II—C50/60) was increased in comparison with FBS 1 (group I—C20/25); however, in relation to the entire reinforced concrete structure (also taking into account the emissions associated with the consumption of reinforcing steel), the opposite result was received: the use of concrete from group II in this case reduced the emissivity by about 6.5%. A similar relationship could be observed for RAC 2 concrete with respect to HPC: the reduction was 1.5%, and for FBS 1 compared to HPC and HPSCC, the reduction was 8.7% and 4.1%, respectively. This indicates the need to take a holistic approach to the selection of concrete type and to consider not only the GHGs emissions per 1 m^3 of concrete but also the values for the entire structure and the emissions associated with the use of reinforcing steel. It should be noted that most often, besides achieving lower emissions, implementing carbon reduction measures also results in a reduction in construction costs and labor intensity. This leads to the conclusion that it is beneficial to combine carbon footprint analysis with cost and labor intensity analysis of construction processes, as highlighted in references [9,83].

4. Conclusions

Despite the ongoing development of methodologies for calculating the carbon footprint, the deficiencies of a unified methodological approach are still apparent. Another perceived problem is the low availability and narrow scope of GHGs emissions databases. An analysis of 15 different concrete mixtures used for a sample reinforced concrete structure showed the following conclusions.

1. The greatest impact on the carbon footprint had the composition of the concrete mix (phase A1), including primarily the type and amount of cement, which indicated the need to take low-carbon measures especially in this area.
2. The use of industrial waste and recycled aggregate helps reduce the carbon footprint of concrete.
3. At the initial stage of construction assessment, the simplified method (phases A1–A3) seems to be a sufficient method for the selection of concrete in terms of its lowest emissivity.
4. On average, approximately 10% of the total carbon footprint emissions over the entire life cycle of the concrete were related to the incorporation of the concrete mixture at the construction site (phases A4–A5) and the demolition of the concrete at the end of its life cycle (phases C1–C4) in the analyzed construction.
5. The share of reinforcing steel in the total CF of the analyzed structure amounted to an average of 15%.
6. Depending on the location of the facility and its geometry and number of floors, when selecting concrete, it is necessary to consider not only the emissions per functional unit but also the value in relation to the entire structure and the emissivity associated with the consumption of reinforcing steel. This is because differences in the amount of material used due to the concrete's strength class can significantly reduce the total carbon footprint emissions.
7. After the implementation of CF reduction measures for phase A1, the impact of transportation, construction site processes, and demolition processes can be considered significant and important to reduce GHGs emissions for these life cycle phases.
8. A correct evaluation of emissions offers a chance to recognize the primary sources and crucial regions that demand the implementation of low-emission procedures. From this standpoint, the analysis presented in this study could assist future researchers, especially when carrying out computations for concretes where binding materials other than Portland cement dominate.
9. There is a need to develop unambiguous guidelines for estimating GHGs emissions that also consider the sources of energy production required primarily for the manufacture of cement, as a result of the specific nature of individual countries' energy mixes.
10. The analysis of the emissivity of a particular construction-material solution is done on a case-by-case basis, as it depends on the location of the structure and factors such as transportation distance and energy sources that vary between countries and are required to produce specific construction materials.
11. The authors point out that the results are subject to uncertainties due to the assumptions made, e.g., regarding materials for which national EPDs were not available (values may vary between regions due to different energy sources), the transport distance assumed, and the calculation of the structure for a specific location (specific climatic loads, ground conditions).

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