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Article

Investigating the Effects of Concrete Mix Design on the Environmental Impacts of Reinforced Concrete Structures

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Abstract: This study examines the impact of mix design parameters on the environmental effects of producing concrete and reinforced concrete buildings by conducting a life cycle assessment (LCA) and carbon footprint analysis (CFA). The study is limited to the cradle-to-gate phase, including the extraction and production of raw materials for concrete production, as well as concrete and rebar production, material transportation, and delivery to the construction site for reinforced concrete structures. Three concrete mix designs based on the American Concrete Institute (ACI) 211-09 standard, with compressive strengths of 20, 30, and 40 MPa, were analyzed. The results indicate that cement was the primary contributor to environmental impacts, accounting for approximately 90% of the carbon footprint. Sand, gravel, and admixtures followed cement in their impact on LCA results. Water usage in concrete production had a negligible effect on LCA indicators. Moreover, to determine how mix design parameters impact the carbon footprint of reinforced concrete buildings, three four-story structures were designed. The results show that in reinforced concrete buildings, concrete was a significant contributor to environmental impacts, accounting for over 50% of all indicators in the IMPACT 2002+ and CML baseline 2000 methods, except for resources and acidification. The study underscores the importance of considering mix design parameters in reducing the carbon footprint of reinforced concrete buildings and provides valuable insights into their environmental impacts. The findings indicate that cement is the main driver of environmental impacts in both assessment methods, accounting for around 90% of the carbon footprint. Additionally, concrete plays a substantial role in environmental effects, contributing to over 50% of all indicators measured in the methods used for evaluating environmental impacts.

Keywords: life cycle assessment (LCA); reinforced concrete structure; environmental impacts; concrete mix design

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1. Introduction

In contemporary times, the phenomenon of global warming, characterized by the sustained escalation of the Earth's mean surface temperature attributed to the accumulation of greenhouse gases (GHGs) within the atmosphere, presents a significant predicament for humankind [1,2]. GHGs can retain solar heat that would otherwise be released back into space, causing a gradual increase in temperature. The repercussions of global warming are diverse and encompassing, exerting a perceptible influence on a global scale. Some of the most significant impacts are extreme weather events, health impacts, rising sea levels, loss of biodiversity, and economic impacts [3,4].

The building sector generates a considerable proportion of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), which is discharged during the production of construction materials, transportation of these materials to the building site, and the energy consumption during the construction and operational phases [5–9]. According to the Global Alliance for Buildings and Construction, buildings account for 39% of global energy-related carbon dioxide emissions [10]. In addition, the construction sector yields a notable quantity of refuse, encompassing construction and demolition residuals. Upon their deposition in landfills, these residuals emit methane, a highly potent GHG.

One of the most commonly utilized construction materials in the building industry is concrete [11–13], owing to its strength, durability, and versatility. It is used in the construction of foundations, walls, floors, bridges, and many other structures. Its importance in the construction industry cannot be overstated, as it forms the backbone of modern infrastructure. However, the production of concrete has significant environmental impacts [4,14]. The manufacturing procedure includes obtaining and treating natural resources such as limestone and clay, which generates large amounts of GHG emissions. Additionally, the production process consumes significant amounts of energy, and the transportation of the raw materials and the finished product can further contribute to carbon emissions. Furthermore, the use of concrete in construction can also have negative environmental impacts, such as resource depletion, energy consumption, the destruction of natural habitats during quarrying, and the generation of construction waste when structures are demolished.

Mix design and strength of concrete are critical factors in the design of reinforced concrete buildings [15,16]. The mix design of concrete refers to the process of determining the proportions of various ingredients such as cement, aggregates, and water to achieve the desired properties of the concrete, such as workability, strength, and durability. A well-designed concrete mix can help ensure that the concrete achieves its desired strength and durability, which are crucial in the construction of reinforced concrete buildings.

Numerous scholars have employed life cycle assessment (LCA) to explore the ecological repercussions of various concrete mix design configurations. This approach facilitates the identification of possible environmental problem areas and offers valuable perspectives on how to mitigate such impacts. LCA presents a comprehensive analysis of the environmental impacts of a product or process by taking into account a wide range of factors, including water use, energy consumption, land use, GHG emissions, and other environmental indicators.

In 2009, Huntzinger and Eatmon [17] utilized SimaPro 6 software to examine the environmental effects of four types of cement production, including traditional Portland cement, Portland cement produced with cement kiln dust, blended cement (natural pozzolan), and cement using 100% recycled waste cement kiln dust (CKD). Their findings revealed that CKD decreased cement's environmental impact by 5%. Meanwhile, Van den Heede and De Belie [18] investigated the environmental impacts of green concrete and those of traditional concrete in 2012. They determined that green concrete made from furnace slag causes less contamination than Portland cement-based concrete. In their 2012 study, Habert et al. [19] employed ISO14040-based LCA methodology to compare the environmental impact of high-performance concrete (HPC) and traditional concrete in bridge construction. They found that HPC had a 10% lower environmental impact compared to traditional concrete by employing the SimaPro software and Ecoinvent database. Moreover, the use of HPC in bridge construction materials led to a reduction of GHG emissions by up to 50%. Consequently, the authors concluded that the application of HPC is more environmentally friendly than traditional concrete.

Liu et al. [20] found that reactive powder concrete (RFC) had significantly lower GHG emissions and energy consumption than traditional concrete, with reductions of 64% and 55%, respectively. Faleschini et al. (2014) [21] also found that recycled concrete containing electric furnace arc slag had 35% fewer emissions than concrete made with natural aggregate. According to the study conducted by Celik et al. [22], incorporating fly ash and limestone powder instead of some cement led to the creation of effective concrete that can withstand chloride penetration and also contribute to a reduction in global warming.

Tait and Cheung (2016) [23] used simulation software to assess the environmental impacts of concrete containing different percentages of cement, fly ash, and slag and found that certain mixtures resulted in a 62% and 32% reduction in CO_2 emissions compared to traditional concrete. These studies highlight the potential of sustainable concrete production techniques to reduce the environmental impact of construction projects.

Roh et al. [24] conducted a comparative study of the potential environmental impact of producing recycled and by-product aggregates and to evaluate their cost and environmental impact when used in concrete. The study involved an LCA to compare six types of aggregates, namely natural sand, natural gravel, recycled aggregate, slag aggregate, bottom ash aggregate, and waste glass aggregate, with respect to six potential environmental impacts. They found that concrete incorporating slag aggregate as fine aggregates or bottom ash aggregate as coarse aggregates had lower environmental impacts compared to concrete incorporating natural aggregate, while bottom ash aggregates as fine aggregates resulted in relatively high environmental impacts. Based on these environmental impacts, the environmental cost ranged from 5.88 to 8.79 USD/m^3.

Asadollahfardi et al. [25] investigated the environmental impact of five various types of concrete, namely Geopolymer, microsilica, nanosilica, micro-nano bubble, and ordinary Portland cement. Their results indicated that Geopolymer concrete has a much lower global warming indicator than the other concrete types, with a reduction of nearly 26% compared to OPC concrete. Conversely, microsilica, micro-nano bubble, and nanosilica concrete had increased global warming indicators by approximately 56%, 38%, and 17%, respectively, compared to ordinary Portland cement concrete.

Xing et al. [26] employed the LCA method to assess the ecological impact of 57 concrete products. Furthermore, they compared the environmental performance of virgin aggregate concrete, recycled aggregate concrete, and CO_2 concrete, all of which used the same mix design. Their results demonstrate that the environmental effect of concrete mix design differs significantly, with the global warming potential of unit volume concrete varying from almost 278 to 524 kg CO_2 eq. The study concludes that cement has the greatest environmental impact, while the effects of aggregate content and type, chemical additives, and carbon-conditioning treatment of recycled aggregate on the outcomes are minimal.

Multi-criteria life cycle assessment (MCLCA) is an evaluation framework that goes beyond traditional life cycle assessment (LCA) by considering multiple environmental, social, and economic criteria simultaneously [27]. It provides a comprehensive and holistic approach to assess the sustainability of products, processes, or systems throughout their life cycle. In MCLCA, various impact categories are considered, such as greenhouse gas emissions, energy consumption, water usage, human health impacts, and social equity. By incorporating multiple criteria, MCLCA allows decision-makers to gain a more complete understanding of the trade-offs and synergies between different sustainability dimensions [28]. This approach facilitates the identification of possible environmental and social problem areas, as well as offers valuable perspectives on how to mitigate such impacts. MCLCA provides a robust framework for decision-making, aiding stakeholders in making informed choices towards more sustainable alternatives and promoting a balanced consideration of environmental, social, and economic factors.

Shmlls et al. [29] carried out an extensive assessment of the life cycle and multi-criteria analysis to evaluate the closed-loop recycling of concrete. A comprehensive framework was developed, considering six key performance indicators across technical (e.g., compressive strength at different ages), environmental (e.g., human health, ecosystem quality, climate change, resources), and economic (e.g., costs) aspects. The framework was then analyzed using three multi-criteria decision-making methods: TOPSIS, VIKOR, and EDAS. The findings of this study highlight the simplicity and efficiency of these decision-making techniques, as they required minimal time and effort while providing valuable insights to select the most suitable concrete mixtures.

In order to enhance the precision and reliability of life cycle sustainability assessments, it is recommended that future research endeavors focus on acquiring more detailed and precise data. Recognizing the inherent uncertainty associated with data collection, efforts should be made to gather comprehensive and reliable information. Additionally, to achieve a more comprehensive analysis, it would be advantageous to incorporate additional components of the buildings into the assessment. This would involve considering the entire life cycle of the building, including its construction, operation, maintenance, and end-of-life phases. By expanding the scope of analysis to include a broader range of components, such as building materials, energy systems, water management, and waste management, a more accurate and comprehensive understanding of the sustainability performance of buildings can be achieved. This would enable decision-makers to make more informed choices and implement effective strategies for sustainable building practices [30,31].

Previous studies in the literature have evaluated the significance of mix design parameters; however, they have not provided a clear understanding of which mix design parameters affect the environmental impacts of reinforced concrete structures, nor how they affect them. Thus, the novelty of this research is to comprehensively review the mix design parameters that influence the life-cycle environmental impacts of reinforced concrete structures. The objective of this study is to gain a deeper understanding of how mix design factors affect a building's ecological performance and to enhance design factors that promote environmentally conscious design solutions. In order to achieve this goal, the article is organized as follows: Section 2 explains the methodology for analyzing the environmental effects of a product or service, Section 3 suggests a model description, and Section 4 provides information on the design factors that impact a building's carbon emissions. The article concludes in Section 5.

2. Methodology

2.1. LCA Method

LCA is a technique that evaluates the ecological consequences of a commodity or amenity throughout its entire life, from the collection of raw materials to its disposal at the end of its life span, as stated in references [32–35]. LCA examines every phase of a product's life cycle, including the procurement of raw materials, the manufacturing process, transportation, utilization, and the methods used to dispose of it when it reaches the end of its life. The aim of LCA is to identify potential environmental impacts and provide a holistic understanding of the environmental footprint of a product or service. LCA can be used to support decision-making in various areas, such as product design, material selection, and waste management [36].

The LCA methodology consists of four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation [37]. In the first stage, the goal and scope of the study are defined, including the system boundaries, functional units, and data requirements. In the inventory analysis stage, data are collected on the inputs and outputs of each stage of the product life cycle. The impact assessment stage evaluates the potential environmental impacts of the product or service based on the data collected in the previous stage. Finally, in the interpretation stage, the results of the study are analyzed, and conclusions are drawn. LCA provides a useful method for assessing the environmental sustainability of services and products and identifying opportunities for improvement.

There are three main types of LCA: the cradle-to-grave LCA, the cradle-to-gate LCA, and the gate-to-gate LCA. The cradle-to-grave LCA looks at the entire life cycle of a product, from the extraction of raw materials to its disposal, and evaluates its environmental impact at every stage. The cradle-to-gate LCA, on the other hand, only considers the environmental impact of a product up until it leaves the factory gate. This type of LCA is useful for assessing the environmental impact of manufacturing processes. Finally, the gate-to-gate LCA only evaluates the environmental impact of a single stage in the life cycle of a product, such as transportation or energy production.

Data quality and uncertainty play a crucial role in conducting a reliable and accurate LCA. Ensuring high-quality data is essential to obtain trustworthy results and make informed decisions. In LCA, data quality refers to the reliability, representativeness, completeness, and precision of the collected data. It involves carefully selecting data sources, ensuring their relevance to the assessed system, and verifying their accuracy. Additionally, data should be representative of the specific geographic location, time period, and technology considered in the assessment. Uncertainty is an inherent aspect of LCA due to various factors, including data limitations, assumptions made during the analysis, and inherent variability in environmental impacts.

2.2. Carbon Footprint Analysis (CFA)

CFA is a process of quantifying the amount of GHGs emitted by an individual, organization, or activity over a specified period [38]. It is a useful method for understanding and managing the environmental impact of a particular product or service. The CFA takes into account every step of the product's existence, which encompasses the gathering of raw materials, production, transportation, utilization, and elimination [39]. The carbon footprint is measured in CO_2 equivalents, which represents the amount of carbon dioxide released into the atmosphere that would have the same warming effect as other GHGs, such as nitrous oxide and methane.

CFA is essential in the context of climate change, as it allows individuals and organizations to identify areas of high emissions and prioritize efforts to reduce them. For instance, a business may identify transportation as the biggest source of emissions and work to promote carpooling or switch to more fuel-efficient vehicles. A product manufacturer may prioritize using renewable energy in their manufacturing process or sourcing materials from sustainable sources. By reducing the carbon footprint, individuals and organizations can mitigate their impact on the environment, contribute to the global effort to combat climate change, and potentially save money through increased efficiency and reduced energy consumption [40,41].

Therefore, CFA is a useful method for measuring and managing the environmental impact of products, services, and activities. It provides insight into areas of high emissions, enabling individuals and organizations to prioritize efforts to reduce their carbon footprint, mitigate their impact on the environment, and contribute to global efforts to combat climate change.

3. Model Description

Three four-story reinforced concrete frames that are similar in geometry were designed to analyze how mix design parameters affect the carbon footprint of such structures. All of these frames have a floor height of 3.2 m and use an ordinary moment frame for lateral force resistance. Figure 1 illustrates a 3D view of the structure containing the dimensions of the spans and the levels of the floors.

Three 28-day compressive strength levels of concrete, namely 20, 30, and 40 MPa, were taken into account for the design of the structures. Additionally, the longitudinal rebars specified for reinforcing the concrete elements have a tensile strength of 400 MPa at the yield level. The yield stress of transverse reinforcements was also considered to be 340 MPa. The concrete mixture formulations employed are grounded on the ACI 211-09 standard [42], with the corresponding variables being presented in Table 1.

Table 1. The concrete mix designs based on the ACI 211-09 standard.

Concrete ID	28-Day Compressive Strength (MPa)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	W/C Ratio	Superplasticizer (kg/m^3)
C20	20	259	799	1146	0.69	1.4
C30	30	331	739	1146	0.54	1.7
C40	40	425	660	1146	0.42	2.0

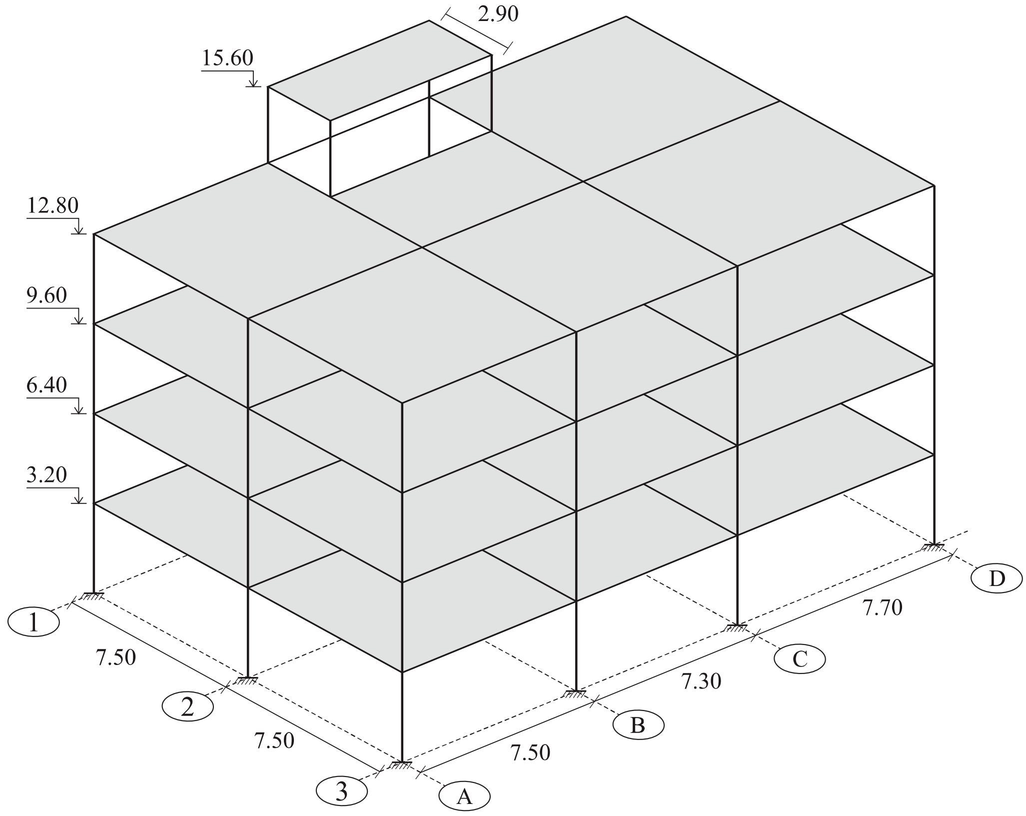

Figure 1. A 3D schematic view of the structures (dimensions are in meters).

To incorporate the dead load of the floors, specifically accounting for the joist beam and block roof, a load of 6.70 kN/m^2 was considered for the roof and a load of 5.35 kN/m^2 for the other stories. Additionally, a partition load of 1.00 kN/m^2 was uniformly distributed on the floors, excluding the roof. The linear dead load of the walls, which ranged from 5.35 kN/m to 7.00 kN/m, was also factored in, depending on their respective position with respect to the floors [43]. Moreover, to account for the live load, values of 1.50 kN/m^2 and 2.00 kN/m^2 were taken into consideration for the roof and other floors, respectively. These structures located in seismic site class II within the city of Tehran were subjected to seismic excitation as the most effective lateral load by means of a static load equivalent to an earthquake coefficient of 0.207 in conformity with Iranian Standard 2800 [44].

The structures have been optimally designed using ETABS software compatible with the Iranian regulations for the design of reinforced concrete structures [45]. According to the designed concrete frames with three different compressive strengths of 20, 30, and 40 MPa, the corresponding amounts of concrete and rebar required for each of them were accurately determined and presented in Table 2. Furthermore, the mass of the concrete blocks comprising the floors was taken into account for LCA and CFA processes as the components of the structural system.

Table 2. The components and procedures employed in each structure's construction.

Concrete ID	Concrete (m^3)	Concrete Block (ton)	Rebars (ton)	Transportation (ton.km)
C20	320	67	38.72	31,796
C30	311	67	35.08	30,111
C40	304	67	33.95	29,348

As depicted in Figure 2, the system boundaries of this study for concrete production and structure production are limited to the cradle-to-gate and gate-to-gate phases, respectively. Concrete production includes extraction and production of raw materials, while the life cycle stages for the production of reinforced concrete structures are the production of the concrete and rebar, in addition to the on-site transportation, which is mentioned in Table 2. It should be noted that only building frames are taken into consideration, while the impacts of masonry and architectural components such as walls, partitions, façade, and floor ceramic are not considered, as they are similar for all three structures.

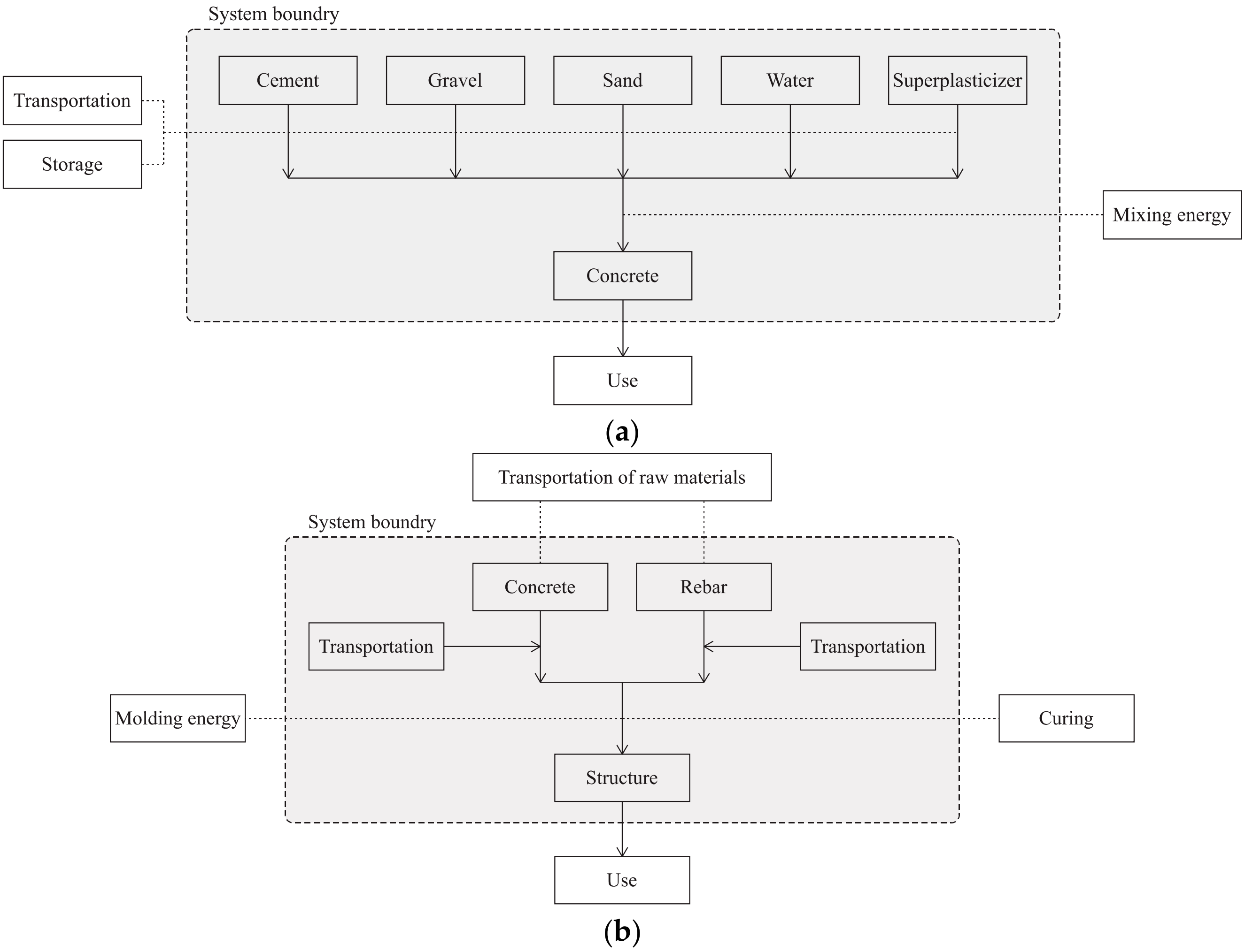

Figure 2. The considered system boundaries for the conducted LCA of (**a**) concrete production (1 m^3), (**b**) structure production.

4. Results and Discussion

In this section, the environmental impacts of concrete with three different mixing designs are examined. Subsequently, the impact of these mixing designs on the LCA of the structures is evaluated. All of the assessments were carried out utilizing SimaPro 9.0.0.48 software developed by PRé Consultants and relied on the Ecoinvent v. 3.5 databases for Life Cycle Inventory (LCI). In this regard, two distinct methodologies were employed, namely IMPACT 2002+ and CML baseline 2000.

4.1. The Environmental Impacts of the Concrete Mix Design Parameters

Table 3 presents the results of the LCA conducted on 1 m^3 of concrete with compressive strengths of 20, 30, and 40 MPa, using two different methods: IMPACT 2002+ and CML baseline 2000. The results reveal that cement consumption has a significant influence on all environmental indicators of concrete. For instance, an increase in cement usage in C40 concrete compared to C20 concrete is associated with respective increases of 43.73%, 56.37%, and 41.31% in human health, climate change, and human toxicity indicators. Similarly, the corresponding increased values for C30 concrete compared to C20 concrete are 19.00%, 24.47%, and 17.99%, respectively. Additionally, the results indicate good compatibility between the carbon footprint calculated using two criteria, IMPACT 2002+ (climate change) and CML baseline 2000 (global warming), with a difference not exceeding 1.18% for concrete with different mixing designs.

Table 3. Total environmental damage impacts for different concrete mix designs.

Method		Unit of Measurement	C20	C30	C40
IMPACT 2002+	Human health	DALY	0.000133	0.000158	0.000191
	Ecosystem quality	PDF.m^2.yr	42.129	49.750	59.662
	Climate change	kg CO_2 eq.	267.193	332.572	417.819
	Resources	MJ primary	1524.054	1810.962	2183.168
CML baseline 2000	Acidification	kg SO_2 eq.	0.66281	0.79334	0.96335
	Eutrophication	kg PO_4 eq.	0.17710	0.21087	0.25482
	Global warming	kg CO_2 eq.	270.366	336.409	422.518
	Human toxicity	kg 1,4 DB eq.	68.473	80.793	96.761

The term “strength per unit impact” for concrete refers to the measure of compressive strength achieved by the concrete relative to its environmental impact. It quantifies the strength performance of the concrete in relation to the resources consumed, energy expended, and emissions generated during its life cycle. Table 4 presents the strength per unit impacts of different mix designs.

Table 4. Strength per unit impact for different concrete mix designs.

Method		C20	C30	C40
IMPACT 2002+	Human health	150,375.9	189,873.4	209,424.1
	Ecosystem quality	0.475	0.603	0.670
	Climate change	0.075	0.090	0.096
	Resources	0.013	0.017	0.018
CML baseline 2000	Acidification	30.2	37.8	41.5
	Eutrophication	112.9	142.3	157.0
	Global warming	0.074	0.089	0.095
	Human toxicity	0.292	0.371	0.413

Figure 3 illustrates the share of concrete constituents in different mixing designs based on two methods, IMPACT 2002+ and CML baseline 2000. Cement is found to be the primary contributor to the environmental impacts in all indicators of these two methods, constituting approximately 90% of the carbon footprint. Following cement, sand, gravel, and admixtures have the greatest impact on the LCA results. For instance, in terms of the human health category, the share of cement, sand, gravel, and admixtures in C20 concrete is 69.98%, 19.91%, 9.01%, and 1.04%, respectively. It is noteworthy that water usage in concrete has a negligible effect on LCA indicators. Moreover, although the amount of sand used remained constant in the presented mixing design, an increase in cement content led to a decrease in the contribution of sand to the environmental effects.

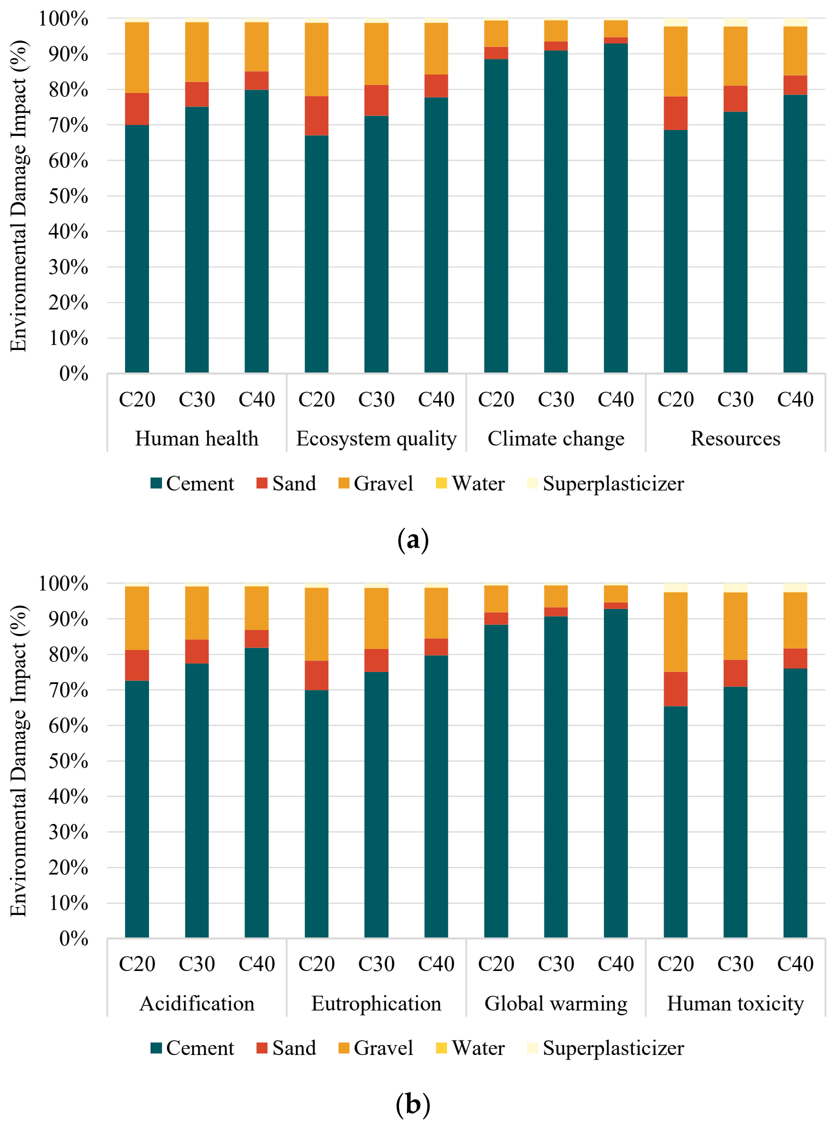

Figure 3. LCA results for different concrete mix design parameters based on the (**a**) IMPACT 2002+, (**b**) CML baseline 2000.

4.2. The Environmental Impacts of Structures for Different Concrete Mix Designs

Increasing the compressive strength of concrete enables a reduction in cross-sectional areas, leading to lighter structures. However, this reduction in raw material usage is accompanied by an increase in the proportion of energy-intensive constituents. In this section, the environmental effects of three buildings designed using the mixing design described in the previous section are examined. The LCA results for a one-square meter structure with three compressive strengths of 20, 30, and 40 MPa are presented in Table 5. Two methods, namely IMPACT 2002+ and CML baseline 2000, are used to conduct the assessment. The results indicate that the compressive strength of concrete has a significant impact on all environmental indicators. As the compressive strength of concrete increases from 20 to 40 MPa, the associated environmental indicators for human health, climate change, and human toxicity increase by 12.58%, 19.49%, and 20.38%, respectively. For example, the building constructed with C30 concrete exhibited increases of 3.54%, 6.60%, and 8.14% for human health, climate change, and human toxicity indicators compared to the building constructed with C20 concrete.

The analysis also reveals good compatibility between the amount of carbon footprint calculated based on two criteria: IMPACT 2002+ (climate change) and CML baseline 2000 (global warming). The difference between these two methods for concrete with different mixing plans is less than 2.01%.

Table 5. Total environmental damage impacts for one square meter of the different buildings designed by concrete mix designs.

Method		Unit of Measurement	C20	C30	C40
IMPACT 2002+	Human health	DALY	0.000063	0.000066	0.000071
	Ecosystem quality	PDF.m^2.yr	16.194	17.287	19.128
	Climate change	kg CO_2 eq.	123.190	131.326	147.194
	Resources	MJ primary	1085.988	1078.720	1133.345
CML baseline 2000	Acidification	kg SO_2 eq.	0.41500	0.41793	0.44504
	Eutrophication	kg PO_4 eq.	0.06412	0.06925	0.07759
	Global warming	kg CO_2 eq.	125.672	133.784	149.778
	Human toxicity	kg 1,4 DB eq.	25.032	27.070	30.132

Figure 4 presents the share of building structure components under different mix designs, evaluated by the IMPACT 2002+ and CML baseline 2000 methods.

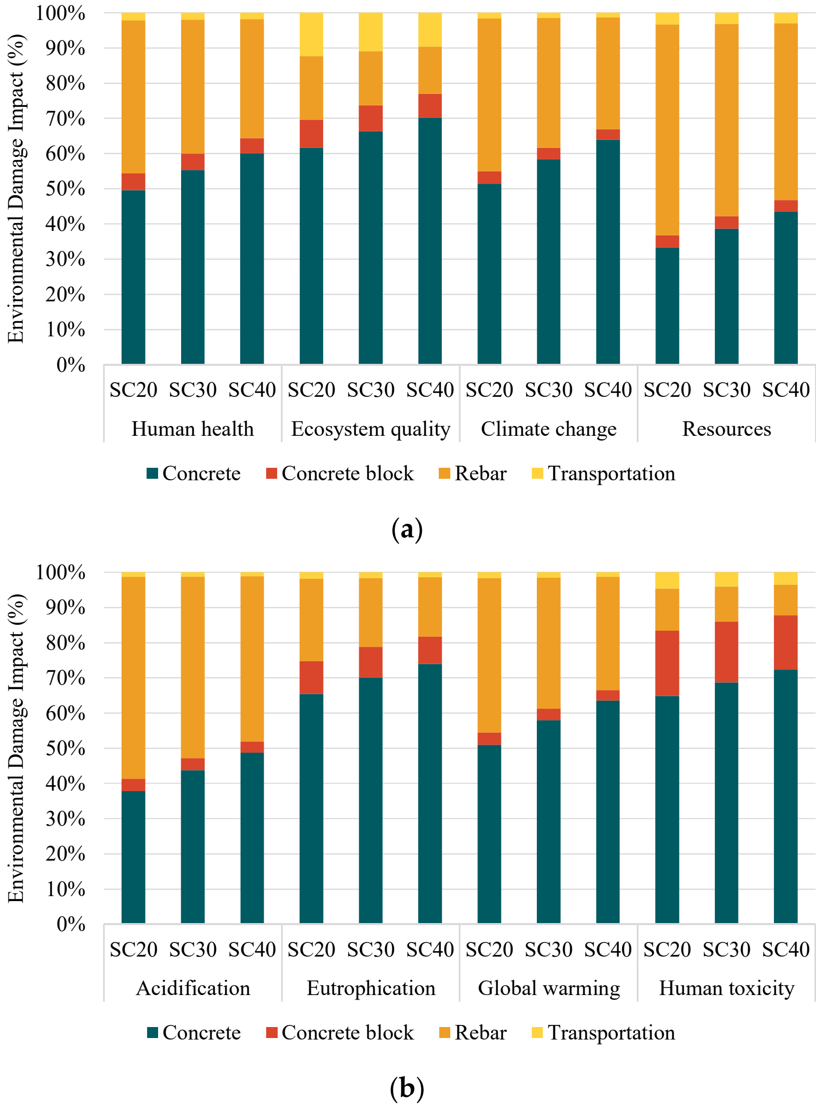

Figure 4. LCA results for different structures according to the (**a**) IMPACT 2002+, (**b**) CML baseline 2000.

Concrete is a significant contributor to environmental effects, constituting over 50% of all indicators in these two methods, except for resources and acidification. Notably, the carbon footprint index reveals that the 20 MPa concrete building has a share of approximately 51%, while the building with 40 MPa concrete has a share of about 64%. Meanwhile, the environmental impact of the used rebars outweighs that of other building structure components in the resources and acidification indices. However, the significance of this impact decreases as the compressive strength of concrete in the building increases, reducing the need for rebar. Furthermore, transportation plays an insignificant role in all indicators, except for ecosystem quality, where it has a share of approximately 11% among environmental factors.

5. Concluding Remarks

This study investigates the impact of mix design parameters on the environmental impacts of reinforced concrete buildings. The scope of this study is restricted to the cradle-to-gate phase. This encompasses the extraction and manufacture of raw materials used in concrete production, as well as the manufacturing of concrete and rebar and the transportation of these materials to the construction site for reinforced concrete structures. The study uses two methods, IMPACT 2002+ and CML baseline 2000, to conduct LCA analyses. For this purpose, three compressive strengths of concrete ranging from 20 to 40 MPa in increments of 10 MPa are considered. The mix designs used are based on ACI 211-09. The results show that cement is the primary contributor to the environmental impacts in all indicators of these two methods, constituting approximately 90% of the carbon footprint. Following cement, sand, gravel, and admixtures have the greatest impact on the LCA results. The results indicate that an increase in cement usage is associated with an increase in human health and human toxicity indicators. The study also found good compatibility between the carbon footprint calculated using two criteria, IMPACT 2002+ (climate change) and CML baseline 2000 (global warming), with a difference not exceeding 1.18% for concrete with different mixing designs.

To analyze how mix design parameters affect the carbon footprint of such structures, three four-story reinforced concrete buildings were designed. These buildings have a floor height of 3.2 m and use an ordinary moment frame for lateral force resistance. While increasing the compressive strength of concrete can lead to lighter structures, it also results in an increase in energy-intensive materials, which can have negative environmental effects. The study examined the environmental impact of three buildings constructed using different strengths of concrete. The results show that the compressive strength of concrete had a significant impact on environmental indicators, including human health, climate change, and human toxicity. As the compressive strength increased, so did the associated environmental impacts.

Concrete is a significant contributor to environmental effects, comprising over 50% of all indicators in the methods used to assess environmental impacts. The carbon footprint of a building constructed with 20 MPa concrete had a share of approximately 51%, while the building with 40 MPa concrete had a share of about 64%. The impact of steel used in building structures outweighed that of other components in the resources and acidification indices, although its significance decreased with the increasing compressive strength of concrete, which reduced the need for rebar.

Transportation played a minor role in all indicators, except for ecosystem quality, where it had a share of approximately 11% among environmental factors. The analysis also revealed good compatibility between the amount of carbon footprint calculated based on two methods: IMPACT 2002+ (climate change) and CML baseline 2000 (global warming). Overall, the study highlights the importance of considering the environmental impact of building materials, particularly concrete, in construction projects.

While it is true that concrete with higher compressive strength typically results in increased environmental impacts due to the higher cement content needed, it is crucial to consider the broader context. Buildings constructed with higher compressive strength often require smaller amounts of concrete, which can help mitigate some environmental concerns. However, it is worth noting that the energy-intensive processes involved in achieving higher compressive strength contribute to elevated carbon emissions. As a result, buildings with higher compressive strength can indeed have greater overall environmental impacts when compared to those with lower compressive strength.

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