Exploring the Viability of Utilizing Slag Waste in Concrete through LCA: A Case Study in Giessen, Germany

Mohammed Hamdallah[1], Jaime Cunha[2, *], Sonaila Qazi[3], Jarosław Górecki[4]

1. PhD Researcher, Department of Civil and Environmental Engineering, University of Iceland, Reykjavík, Iceland; Founder & CEO, OptiDesign ehf., Reykjavík, Iceland.
2. Assistant Lecturer, Faculty of Engineering (FEUP), University of Porto, Porto, Portugal; Researcher, CONSTRUCT – Institute of R&D in Structures and Construction, Porto, Portugal
3. Climate Tech Specialist, Renewables First, Islamabad, Pakistan; Principal, YouTopia's Studio, Peshawar, Pakistan.
4. Associate Professor, Bydgoszcz University of Science and Technology, Bydgoszcz, Poland

*mah118@hi.is

Abstract

According to statistics from the VDI Centre for Resource Efficiency, approximately 30.1 million tons of cement were utilized for construction purposes in Germany in 2020, resulting in an estimated emission of 28 million tons of CO2. Given that concrete is a key material in almost 30% of residential construction, it is imperative to seek methods to reduce cement and clinker usage. One promising avenue involves integrating waste materials into concrete, offering the dual advantage of lowering cement consumption while effectively managing industrial waste. However, the practicality of this approach heavily relies on the availability and quantity of waste materials. To delve deeper into this concept, a study was conducted in Giessen, Germany, with a focus on managing waste from local steel mills, which produce approximately 0.6 tons of waste per ton of steel. This waste encompasses various materials such as steelmaking slag, electric arc furnace dust, mill slag, and zinc sludge. The study examined four concrete scenarios, each involving different levels of cement substitution with Ground Granulated Blast-Furnace Slag (GGBFS). These scenarios included Ultra-High-Performance Concrete (UHPC) with 40% substitution, Conventional Concrete (CC) with 40% and 20% substitution, and CC without waste valorization serving as the control mixture. Evaluations spanning 100 and 200-year lifespans indicated that CC with 40% GGBFS had the least environmental impact over a century. However, over a 200-year period, the durability of UHPC positioned it as the most environmentally friendly option in terms of embodied energy, considering the respective design lifespans of both mixtures. Further analysis, factoring in the reduction in reinforcement within the UHPC mixture, however, it still has the highest environmental for the 100-year design life span (without considering the durability factor).

Keywords: *LCA, Concrete, Waste valorization, Slag mill, GBBFS, UHPC versus CC.*

1. Introduction

The construction industry is a significant contributor to global carbon emissions, with cement production being a notable source. According to statistics from the VDI Centre for Resource Efficiency ("Construction Industry," VDI Zentrum Ressourceneffizienz, n.d.), Germany utilized 30.1 million tons of cement for building construction in 2020, resulting in an estimated 28 million tons of CO2 emissions. With nearly 30% of residential construction in the country using concrete, efforts to mitigate these emissions are crucial in the face of climate change, and sustainable alternatives are actively being sought.

The potential of using industrial wastes (silica fume, granulated blast-furnace slag, and fly ash) as substitutes for cement in creating ultra-high-performance concrete has been investigated to recognize the performance regarding mechanical, durability, and micro-structural characteristics. Ultra-high-performance concrete (UHPC) has emerged as a promising solution, offering the potential to reduce the environmental footprint of construction. The incorporation of industrial by-products such as silica fume, granulated blast-furnace slag, and fly ash as cement substitutes has been a focal point of recent research (Abdellatief et al., 2023). These materials not only improve the mechanical properties of concrete but also contribute to environmental sustainability.

The steel industry, a significant waste generator, produces steelmaking slag, electric arc furnace dust, mill slag, and zinc sludge. For every ton of steel produced, approximately 0.38 tons of slag waste is generated (Birat, 2020). The utilization of Blast Ground Furnace Slag (GGBFS) as a cement replacement has been studied for its positive impact on concrete properties and environmental benefits. Blending slag with Portland cement can immobilize hazardous elements, with organic additives like citric acid enhancing this effect (Branca et al., 2020). Slag's granular form, suitable for use in Portland cement, offers reduced energy consumption, carbon emissions, and conserves natural resources (Parron-Rubio et al., 2019). The shape of the slag waste after the milling process is shown in Figure 1.

The strategic location of steel production facilities near construction zones in Giessen, Germany, offers a valuable chance to repurpose slag waste, as depicted in Figure 2. This method is in harmony with the circular economy's objectives to reduce waste and enhance the efficient use of resources (Nuñez-Cacho et al., 2018). Building upon existing research, this study investigates the incorporation of industrial waste into UHPC, assessing its impact on the material's structural robustness and ecological footprint (Tiecher et al., 2019; Teh et al., 2018). The goal is to develop the most eco-friendly concrete variant for a case study in Giessen, evaluating both environmental factors and performance metrics for two types of concrete—UHPC and conventional concrete (CC)—that include Ground Granulated Blast Furnace Slag (GGBFS) as a component.

Figure 1. Industrial slag waste after ball milling and sieving.

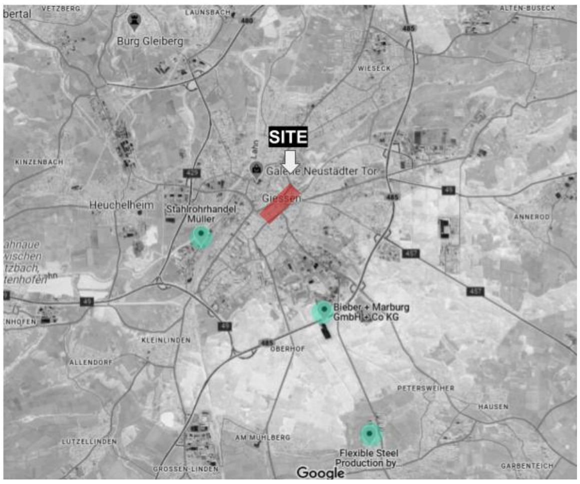

Figure 2 - The distribution of steel mill factories in Giessen, Germany.

2. Methodology

The ISO 14040 standard outlines the LCA methodology across four distinct phases: goal definition, life cycle inventory (LCI) analysis, impact assessment, and interpretation. In the goal phase, the study's context is established, followed by the identification of raw materials and inputs in the LCI phase. Subsequently, the impact assessment phase evaluates potential environmental effects, leading to the interpretation phase where results are scrutinized (Colangelo et al., 2018b). Meanwhile, utilizing DLUBAL RFEM software, structural integrity across four scenarios is assessed, while environmental impact is gauged from literature and Environmental Product Declarations (EPDs. Data necessary for the life cycle assessments encompasses production details, including quantity percentages and environmental impacts, as well as distances from production sites to the concrete plant and energy carrier information. This assessment forms the foundation for evaluating optimal scenarios.

2.1. Case Study Description

Situated in the heart of Giessen, the intervention zone occupies a residential enclave near the city center. Driven by an increasing student population, the locale has experienced a pronounced surge in demand for rental accommodations, thereby applying upward pressure on property prices and necessitating a commensurate expansion of residential infrastructure.

The proposed intervention aims to enhance the value of a building with comparatively minimal architectural alteration in contrast to neighboring structures. The randomly selected building holds distinct features highlighted by a lower floor-to-ceiling height, a notable utilization of prefabricated elements on its façade, and a unique architectural design. As the building recently endured renovation, further maintenance has been deemed unnecessary.

The design proposal entails maximizing the utility of the top floor by eliminating the pitched roof and introducing a new level, thereby augmenting the building's efficiency through the addition of extra residential units. This transformation represents a significant enhancement for the existing structure, promising to revitalize its potential.
Moreover, the intervention is designed to elevate the building's structure as a landmark by employing materials that are either recycled or locally sourced, thereby mitigating their environmental footprint. This commitment to sustainability underscores the project's conscientious approach towards minimizing its ecological impact while simultaneously adding value to the urban landscape. The details of the existing structure are given below:

- Address: Loberstrasse 5a, Giessen (Germany).
- Year of construction: 1995 to 2006.
- Total Floor Area: 1410 m2.
- Levels: 4 + attic
- Program: Residential
- Material: concrete structure with brick masonry and plaster.

2.2. Goal and Scope Definition

Through the comparison of four different mix proportions of concrete with various extents of slag waste replacement, it is crucial to determine a baseline for the standardization of the proposed material. In this case study, that baseline (CC) is the C30/37 in Germany that is currently conventionally used. The additional materials are thus increased in the waste replacement in increments of 40% and 20% with CC and 40% with UHPC and a comparison is drawn of their performance in a 100- and 200-year design service life for environmental sustainability assessment.

The chosen scenarios for comparison are:

- Control Mixture: The benchmark of CC in Germany (thinkstep AG, 2018).
- Mixture 1: UHPC with 40% slag waste valorization (Abdellatief et al., 2023).
- Mixture 2:CC with 40% slag waste valorization (Majhi et al., 2018).
- Mixture 3:CC with 20% slag waste valorization (Rahla et al., 2019a).

The design for the four mixtures was derived from existing literature, as outlined in Table 1.

Table 1. Mix. design of concrete

Mixture type (GGBFS waste substitution percentage)	Components types (based on the literature)																			
	Cement (Mix1: CEM I 52.5 N - Mix2: grade 43 - IS: 8112 standards)		Sand (river sand)		Coarse aggregate (Mix 2: granite type)		Slag waste		Silica Fume		Steel fibers		Quartz powder		Superplastizer		Water		Density (kg/m3)	Strength after 28 days (Mpa)
	Weight (kg/m3)	Quantity percenatge	Weight (kg/m3)	Quantity percenatge	Weight (kg/m3)	Quantity percenatge	Weight (kg/m3)	Quantity percenatge	Weight (kg/m3)	Quantity percenatge	Weight (kg/m3)	Quantity percenatge	Weight (kg/m3)	Quantity percenatge	Weight (kg/m3)	Quantity percenatge	Weight (kg/m3)	Quantity percenatge		
Control mixture	C30/37 obtained from ÖKOBAUDAT dataset																			
Mix 1: UHPC 40%	540	19.1%	1271	44.9%	0	0.0%	360	12.7%	135	4.8%	156	5.5%	180	6.4%	24	0.8%	166	5.9%	2832	110
Mix 2: CC 40%	234	9.4%	710	28.6%	1200	48.4%	142	5.7%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	195	7.9%	2481	33.5
Mix 3: CC 20%	312	12.5%	710	28.5%	1200	48.2%	71	2.9%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	195	7.8%	2488	29

2.3. Functional Unit

The study established the functional unit as 1 cubic meter per megapascal (m3/MPa) of concrete to assess the environmental impact relative to each mixture's strength. However, this approach (strength-normalized CF/EE approach) lacked precision in evaluating the environmental impact compared to the material's strength. To address this, structural simulations were conducted to evaluate the environmental impact relative to material strength using m3 as the functional unit. A comparison between the results obtained from both methods was performed. Additionally, the service life ratio of Ultra-High-Performance Concrete (UHPC) to Conventional Concrete (CC) was assumed to be 2 based on existing literature. UHPC demonstrates remarkable durability compared to traditional concrete, attributed to its dense microstructure and high fiber reinforcement concentration, leading to reduced permeability to water and chloride ions, thus mitigating reinforcement corrosion (Robalo et al., 2023). Typically, resistance to carbonation and chloride ingress is indicative of structural service life, although these values must be contextualized with real-world performance (Robalo et al., 2023; Saladi et al., 2023). A comparative analysis was conducted to project the service life of UHPC and CC, focusing on the anticipated time to corrosion initiation. The findings indicated a service life exceeding 100 years for UHPC, contrasting with 17 years for CC and 50 years for High-Performance Concrete (HPC) (service life ratio ≥ 2) (Saladi et al., 2023). Furthermore, another research suggests that UHPC's service life could extend beyond 400 years in environments prone to carbonation-induced corrosion (XC), considering the minimum concrete cover stipulated by Eurocode standards (Robalo et al., 2023). Other studies have evaluated chloride permeability as a durability indicator, revealing significant discrepancies between UHPC and CC. While CC typically exhibits chloride permeability exceeding 2000 Coulombs (Balamuralikrishnan & Saravanan, 2019; Rahla et al., 2019b), UHPC formulations with 40% Ground Granulated Blast Furnace Slag (GGBFS) displayed a permeability of only 93 Coulombs (Abdellatief et al., 2023), indicating a substantial difference in durability. Notably, a permeability of 2000 Coulombs suggests moderate chloride penetration, whereas 93 Coulombs indicates negligible permeability, underscoring UHPC's superior durability compared to CC (Balamuralikrishnan & Saravanan, 2019). It's important to note that workability was not considered in this analysis.

2.4. System Boundaries

The investigation in this study is confined to a cradle-to-gate approach, where the life cycle analysis of the process is broken down into stages A1 to A3. By examining each of the proposed scenarios for these processes, an understanding of the environmental and ecological impact can be maintained. For the comparison's scope, transportation data utilized was obtained from literature sources. However, actual transportation data was gathered, revealing that the real transportation distances are shorter than those utilized in the analysis, as demonstrated in section 2.2.4.2. The boundaries of the system are illustrated in Figure 4.

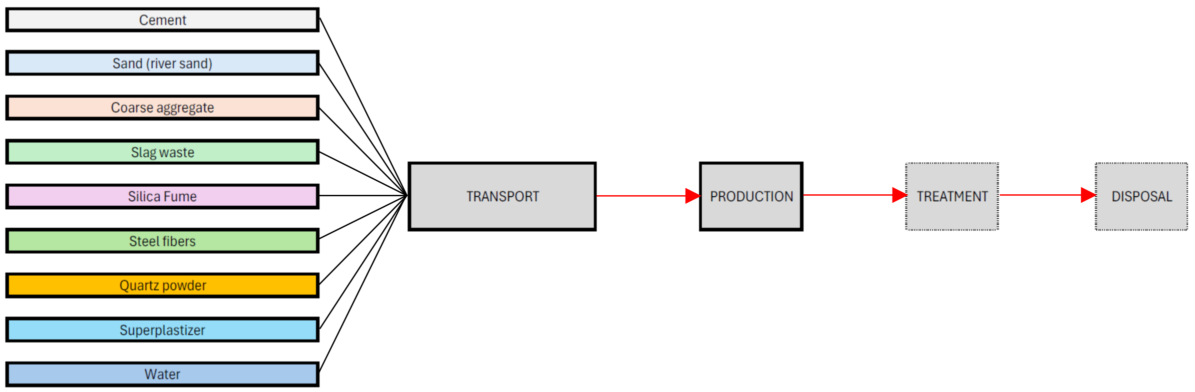

Figure 4. System boundaries of the different types of concrete

2.5. Inventory Analysis (LCI)

In this stage of the Life Cycle Assessment (LCA), primary data were sourced from literature and Environmental Product Declarations (EPDs) due to the absence of suitable datasets for the production stage (A1) of Supplementary Cementitious Materials (SCMs). For comparison, indicators such as Global Warming Potential (GWP) and Resources Use/Abiotic Depletion Potential (ADP) were utilized to represent Carbon Footprint (CF) and Embodied Energy (EE), respectively. The Life Cycle Inventory (LCI) data pertaining to each process are detailed in Figure 5.

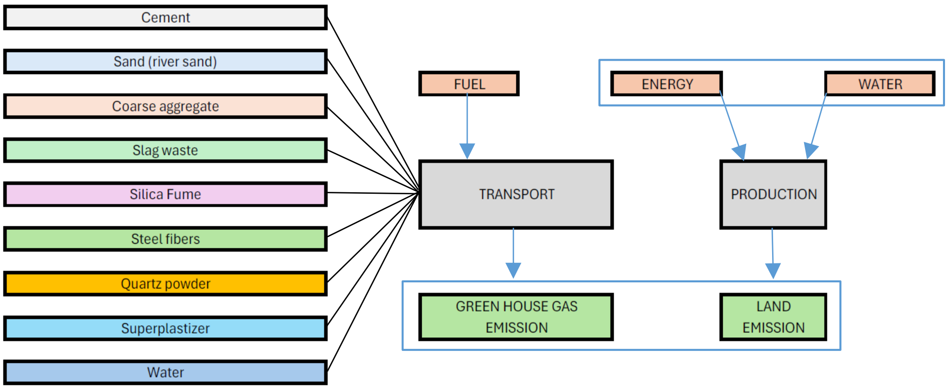

Figure 5. Process of production of different mixtures.

2.5.1. Production of raw materials (A1)

The proposed mixture design for each of the scenarios includes different combinations of CEM I cement (Abdellatief et al., 2023; Sphera Solutions GmbH, 2022), Silica sand (Abdellatief et al., 2023), granite aggregate (Kittipongvises et al., 2016), slag waste (Abdellatief et al., 2023), silica fumes (Abdellatief et al., 2023), steel fibers (Abdellatief et al., 2023), steel rebars (Environmental Product Declaration Steel Rebars, n.d.), and admixtures (Abdellatief et al., 2023). Each of these materials has been selected not only due to its availability in the region and the scope of this study but also due to their expected effective environmental impact in conjunction with the slag waste in concrete. Silica sand and aggregate are sourced from natural deposits or quarries via mining and dredging, and subsequently transported to processing facilities for refinement. Conversely, slag waste is derived as an unusable byproduct from steel mills, and then transported to processing plants for conversion into usable cementitious material for concrete, establishing a symbiotic relationship between the two industries. Besides considering raw materials, transportation, and extraction efficiency also significantly influence the assessment of the material's environmental impact.

2.5.2. Transportation of raw materials (A2)

The transportation of materials from one location to another is a crucial aspect of the overall assessment of its environmental impact. The transportation from extraction sites to processing facilities, then to the concrete plants, and then to the required site contributes to its overall impact. Germany's robust freight transport system allows for the efficient conveying of the required raw materials to sites across the country. The TransAnt wagons or the Deautschebahn Cargo m2 wagons are at the forefront of transporting raw material from steel mills, whereas cement can be transported in 25-ton Bulk-tank-trucks to the chosen site (Elhasia & Noche, 201h3; NACHHALTIGKEITS-BERICHT 2021 HOLCIM DEUTSCHLAND GRUPPE, n.d.). Eventually, The Spenner-Herkules plant with provide the off-site mixing of the required concrete for transportation to the site. The state of Hessen in Germany has several companies and prefabrication factories that provide precast concrete elements for the construction industry. The most prominent ones are in, as shown in Figure 6 summarized in Table 2:

- Holcim concrete and concrete products: estimated travel time of 45min /67kms from location.
- Elementbau Osthessen GmbH: estimated travel time of 1h7m /103kms from location.
- ERATH concrete: estimated travel time of 2h10m / 150kms from location.
- Jordan and Kremer GmbH: estimated travel time of 49min / 65 km from location.

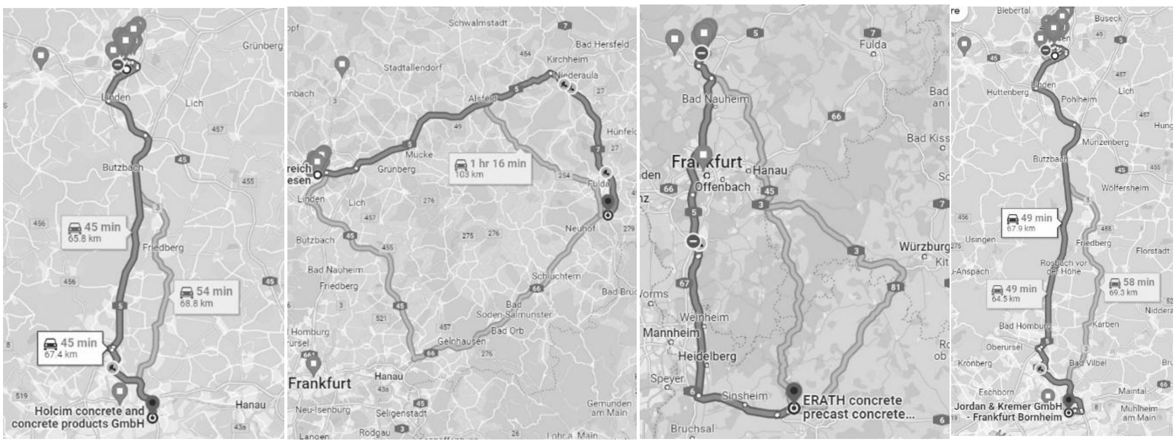

Figure 6. Travel distance between the case study and the different prefabrication plants around Giessen.

Table 2. Travel distances between the material source and the concrete fabrication plants around Giessen.

Material type	Company name	Distance (km)
Silica Sand, Aggregate, Silica Fume	Treiser sand company	15.00
Cement	Baucenter Ruhl GmbH & Co KG	74.20
Slag Waste and Steel Fibers	Bieber + Marburg GmbH & Co KG	70.20

The distances between the different material sources and the concrete fabrication plants are as follows:

- Silica Sand, Aggregate, Silica Fume:

Treiser sand company, 15.0km away from the site, closest supplier to the precast concrete plant of Spenner-Herkules plant in Buseck Giessen which is 11.9km away from the sand and aggregate supplier.

- Cement:

Baucenter Ruhl GmbH & Co. KG, 74.2 km away from Holcim concrete and concrete products, is the most efficient supplier for this case study.

- Slag Waste and Steel Fibers:

Bieber + Marburg GmbH + Co KG, 70.2 km away from Holcim Concrete and Concrete Products, is the most efficient supplier to the chosen site. The steel slag can be procured from this location to the study established.

2.5.3. Manufacturing of raw materials (A3)

According to the concrete mixing plant company, their high-strength concrete class of C55/65 is subject to monitoring class UK3, the direct energy consumption per ton of cement production which is given in their 2021 environmental brochure. Around 1300 MJ of energy is produced for CEM III production of 42,5 N using non-renewable sources of energy such as coal (Die Spenner-Mitarbeiter Vor Dem Spenner Forum, n.d.). Although CEM III is a key component of a sustainable concrete mixture, the production of the clinker required for the cement is an energy-intensive process that requires high temperatures usually achieved through non-renewable sources. The extraction of silica sand and aggregate can also have significant environmental impacts of resource exploitation, soil erosion, and water pollution. Slag waste itself is a waste product produced from steel mills that is typically discarded. However, since this waste has the potential to be used in concrete production, it remains useful. The transformation of the slag waste from a mere by-product to a viable construction material requires the processing of crushing, grinding, and screening to achieve the desired particle size and chemical composition. Silica fume is another cementitious byproduct of a raw material production plant namely silicon. Its production requires high temperatures that could contribute to the energy consumption and emissions of the required concrete. Lastly, steel fibers are an essential part of UHPC that is created through the heavy processing of scrap steel through melting, casting, and extrusion which can also contribute to the overall environmental impact. A separate study was conducted to assess the energy requirements for manufacturing Ultra-High-Performance Concrete and Conventional Concrete, both on-site and in-plant, in Germany. The findings of this study are summarized in Table 3 (Sameer et al., 2019).

Table 3. Electricity, fuel oil, and diesel consumed for the A3 life cycle of the production of 1 m^3 of concrete (Sameer et al., 2019).

Energy Carrier	UHPC		CC	
	Ready-Mix	Precast	Ready-Mix	Precast
	M3Q	M2Q	C35/45	C50/60
	mixing and plant operation			
Electricity (kWh/m3)	7.09		4.43	
Fuel Oil (L/m3)		0.26		
Diesel		0.09		
	Compacting of precast concrete			
Electricity (kWh/m3)		0.90		0.90
	Heat threatment of precast concrete			
Fuel Oil (L/m3)		3.00		

3. Results and Discussion

3.1. Results Based on the Strength Normalized CF/EE Approach

This study explores the utilization of Ultra-High-Performance Concrete (UHPC), known for its durability and strength. The findings reveal that a 40% slag replacement in UHPC (Mix. 1) demonstrates the most efficient environmental impact reduction. However, conventional concrete with 40% slag waste (Mix.2) exhibits the least environmental impact (CF and EE) when considering a design lifespan of 100 years. Specifically, Mix. 2 shows a CF and EE of 5.93 kg/m3/Mpa and 23.79 MJ/m3/Mpa, respectively (as indicated in Table 4). Considering the durability design, which incorporates the service life factor addressed earlier in section 2.2.2, UHPC with 40% waste valorization (Mix.1) shows the lowest CF at 6.34 kg/m3/Mpa, while Mix.2 still displays the least EE (as shown in Table 5). The high cement content and steel fiber usage in UHPC contribute significantly to its environmental impact, along with the use of superplasticizers, as illustrated in Figures 7 and 8.

Table 4. Environmental impact of different concrete mixtures for 100 years design life span.

Environmental impact of different concrete mixtures for 100 years design life span

Mixture type (GGBFS waste substitution percentage)	Cement		Sand (silica sand)		Coarse aggregate (Mix 2: granite type)		Slag waste		Silica Fume		Steel fibers		Quartz powder		Superplastizer		Water		Environmental impact/m3		Strength after 28 days (Mpa)	Environmental impact/m3/Mpa	
	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3		Carbon Footprint (CF) kg/m3/Mpa	Embodied Energy (EE) MJ/m3/Mpa
Control mixture	C30/37 obtained from ÖKOBAUDAT dataset																		283.10	863.90	30.00	9.44	28.80
Mix 1: UHPC 40%	448.20	2592.00	1.27	27.96	0.00	0.00	6.84	571.68	1.89	13.50	232.44	3212.04	0.18	3.96	6.00	434.40	0.03	1.66	696.85	6857.20	110.00	6.34	62.34
Mix 2: CC 40%	191.88	554.58	0.71	15.62	3.48	5.40	2.70	225.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	1.95	198.81	803.05	33.50	5.93	23.97
Mix 2: CC 20%	255.84	739.44	0.71	15.62	3.48	5.40	1.35	112.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	1.95	261.42	875.16	29.00	9.01	30.18

Table 5. Environmental impact of different concrete mixtures for 200 years design life span.

Environmental impact of different concrete mixtures for 200 years design life span

Mixture type (GGBFS waste substitution percentage)	Cement		Sand (silica sand)		Coarse aggregate (Mix 2: granite type)		Slag waste		Silica Fume		Steel fibers		Quartz powder		Superplastizer		Water		Environmental impact/m3		Strength after 28 days (Mpa)	Environmental impact/m3/Mpa	
	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3		Carbon Footprint (CF) kg/m3/Mpa	Embodied Energy (EE) MJ/m3/Mpa
Control mixture	C30/37 obtained from ÖKOBAUDAT dataset																		566.20	1727.80	30.00	18.87	57.59
Mix 1: UHPC 40%	448.20	2592.00	1.27	27.96	0.00	0.00	6.84	571.68	1.89	13.50	232.44	3212.04	0.18	3.96	6.00	434.40	0.03	1.66	696.85	6857.20	110.00	6.34	62.34
Mix 2: CC 40%	383.76	1109.16	1.42	31.24	6.96	10.80	5.40	450.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	3.90	397.61	1606.09	33.50	11.87	47.94
Mix 2: CC 20%	511.68	1478.88	1.42	31.24	6.96	10.80	2.70	225.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	3.90	522.84	1750.32	29.00	18.03	60.36

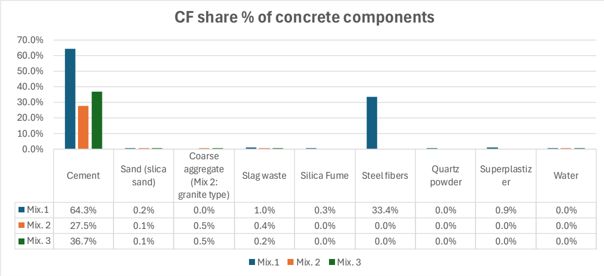

Figure 7. Carbon Footprint (CF) share of concrete components.

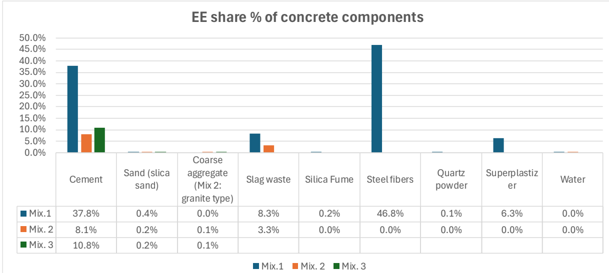

Figure 8. Embodied Energy (EE) share of concrete components.

3.2. Results Based on Structural Simulation

Utilizing Finite Element (FE) analysis, as depicted in Figure 10, the investigation into Mix.1 and Mix.2 considers the influence of reinforcement. Table 6 reveals a notable decrease in both concrete and reinforcement quantities, along with the Carbon Footprint (CF), showing reductions of 54%, 14.8%, and 11%, respectively, over a 100-year design lifespan, with a clear preference for UHPC (Mix.1). However, there is a noticeable rise in Embodied Energy (EE) when compared to the strength-normalized approach. Notably, even without factoring in its durability aspect, UHPC demonstrates the lowest CF, as depicted in Figure 11. Additionally, Figure 12 illustrates the distribution of impact between concrete and reinforcement for both mixtures.

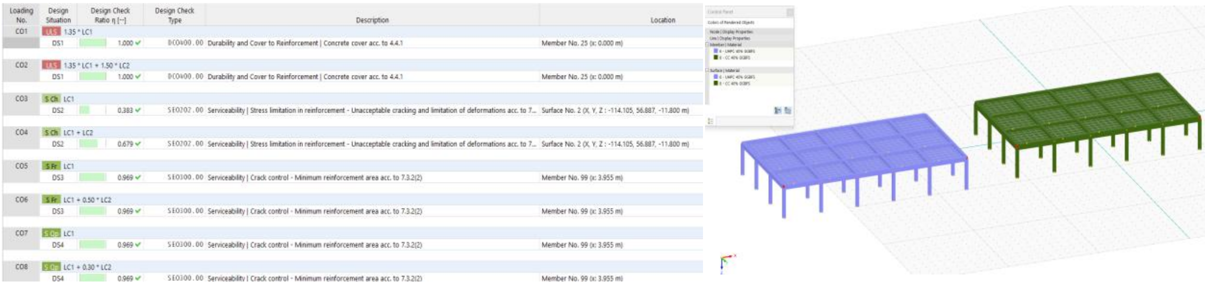

Figure 9. Structural simulation of the case study utilizing Mix.1 and Mix.2 (Blue is Mix.1 and Green is Mix.2).

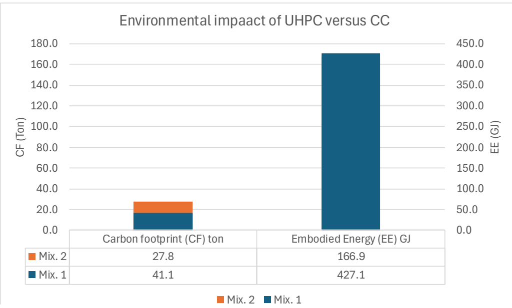

Figure 10. Environmental impact of UHPC versus

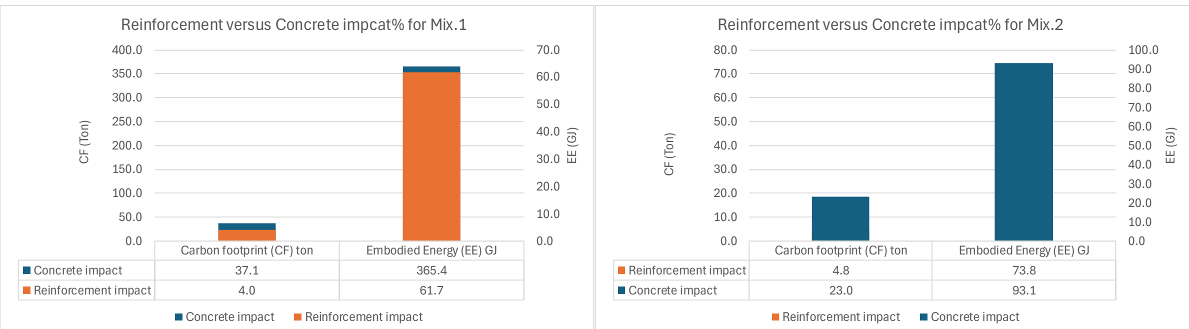

Figure 11. Reinforcement to Concrete impact% for Mix.1 and Mix.2

Table 6. Environmental impact of the case study for 100 years design life span

Environmental impact of the case study for 100 years design life span																		
Mix. Type/impact	Concrete impact					Reinforcement impact					Total impact		Reinforcement to concrete impact %		Reduction in material		Reduction in the environmental impact (Mix.2 to Mix.1)	
	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Quantity (m3)	Carbon footprint (CF) ton	Embodied Energy (EE) GJ	Carbon footprint (CF) kg/m3	Embodied Energy (EE) MJ/m3	Quantity (kg)	Carbon footprint (CF) ton	Embodied Energy (EE) GJ	Carbon footprint (CF) ton	Embodied Energy (EE) GJ	Carbon footprint (CF)	Embodied Energy (EE)	Concrete	Reinforcement	Carbon footprint (CF)	Embodied Energy (EE)
Mix 1: UHPC 40%	696.9	6857.2	53.3	37.1	365.4	0.9	13.8	4472.8	4.0	61.7	41.1	427.1	10.72%	16.89%	54.0%	16.4%	32.4%	60.9%
Mix 2: CC 40%	198.8	803.0	115.9	23.0	93.1	0.9	13.8	5347.6	4.8	73.8	27.8	166.9	20.66%	79.30%				

4. CONCLUSIONS

Considering the increasing demand for sustainable construction solutions across various industries, the exploration of durable materials becomes imperative. Ultra-high-performance concrete (UHPC) stands out as a viable long-term option for civil structures, especially when incorporating waste materials into their aggregate to reduce environmental impact. This study lays the groundwork for further investigating the utilization of slag waste in both Conventional Concrete (CC) and UHPC, emphasizing the construction industry's potential to foster ecological benefits through innovative approaches. Despite UHPC's structural advantages, its material requirements may not exceed those of CC, thanks to its efficiency in cementitious content and fine particle distribution. Substituting aggregate with slag waste from steel mills enhances this efficiency. Comparative analysis between UHPC with 40% replacement and CC with 20% replacement highlights UHPC's lower environmental impact, alongside its effectiveness over 100- and 200-year lifespans, providing a robust framework for enduring structures.

However, we are aware of the imperfections resulting from the assumptions made. Particularly noteworthy is the challenge regarding the repeatability of the obtained composition in the part regarding recycled material. The biggest challenge today is obtaining homogeneous waste input. Unfortunately, many practical examples show that this is only possible in limited batches (e.g. one silo). Therefore, stress should be put on ensuring the same composition of the concrete mixture to obtain comparable concrete parameters.

Future research directions could entail delving deeper into understanding the service life and conducting uncertainty analyses using sophisticated models such as life-365. The study's analysis highlights the potential of Ultra-High-Performance Concrete (UHPC) in mitigating environmental impact, particularly when incorporating 40% slag replacement. However, it's noteworthy that even with this substitution ratio, UHPC doesn't outperform conventional concrete with 40% slag waste (Mix.2) in terms of Embodied Energy (EE). Mix.2 demonstrates the lowest Carbon Footprint (CF) values over a 100-year lifespan, showcasing its environmental efficiency. Nevertheless, UHPC with 40% waste valorization (Mix.1) exhibits the lowest CF over a 200-year lifespan, while Mix.2 maintains its superiority in EE, indicating the intricate balance required between structural performance and environmental concerns in the concrete mix design. The elevated environmental impact of UHPC is primarily attributed to its cement content, underscoring the imperative for further optimization and research endeavors in sustainable construction materials.

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