CO_2 emissions of low cement UHPC

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Summary
Ultra-High Performance Concrete (UHPC) has been studied as an alternative for bridge construction, enabling the creation of lighter and more durable structures. However, its high cement content (around 900 kg/m³) increases CO_2 emissions and production costs. To address this, supplementary cementitious materials (SCMs), such as rice husk ash (RHA), are studied to reduce cement use due to their high reactivity. This paper investigates the environmental impact of low-cement UHPC (LC-UHPC) made with 60% replacement of cement by RHA, comparing it to conventional concretes (CC) and high strength concretes (HSC). A Life Cycle Assessment (LCA) was performed to calculate CO_2 emissions for 1 m³ of concrete, comparing UHPC, LC-UHPC, CC and HSC. LC-UHPC reduces CO2 emissions by nearly 50%, matching the level of HSCs. UHPC is more efficient in cement use and CO_2 emissions despite having higher emissions per cubic meter than conventional concretes.

1 INTRODUCTION

Ultra-High Performance Concrete (UHPC) is a material with excellent mechanical properties, with a compressive strength of 120 MPa [1], and high durability, which are obtained by a combination of high particle packing and a water-cement ratio between 0.15 and 0.25 [2].

The combination of higher mechanical properties and durability makes it possible to produce slender and more durable structures, thus the use of UHPC has been studied as a greener alternative for bridge construction [3]. However, the high packing density is obtained by using a combination of different powders, the absence of coarse aggregate and, more importantly, a high use of cement, around 900 kg/m^3.

With the high amount of cement and the low water/binder ratio, not all cement is hydrated and it ends up acting as fillers in the microstructure [4]. Because of that, part of the cement can be removed to improve the eco-efficiency of UHPCs. Various materials have been studied in the literature as supplementary cementitious materials (SCMs) for UHPCs, such as Fly Ash (FA) [5–7], Ground Granulated Blast Furnace Slag (GGBFS) [8–10]. Since there is a shortage of FA and GGBS different studies have been conducted to produce alternative for the materials, being Calcinated Clay [11,12], Limestone Powder more famous examples. However, agricultural wastes, such as Rice Husk Ash (RHA) have also been considered for cement replacement in greener concretes.

Rice husk ash is a subproduct of the agricultural industry. It has over 90% of amorphous silica and it is a viable option as pozzolanic material for cement reduction without negatively affecting the mechanical properties of concretes. However, the lower density, higher specific surface area and higher porosity make it difficult to use the material in high substitutions percentages. Percentages from 5% to 50% are studied in literature, with 40% being the optimal substitution ratio in UHPCs [13].

Based on that, this study aimed to produce low-cement UHPCs (LC-UHPC) with a high substitution rate to assess the mechanical properties and CO_2 emissions of the mixture, comparing it to conventional concrete and high-strength concrete mixtures found in the literature. This study explores the use of RHA at a high replacement rate of 60% for the production of LC-UHPC, which has not been extensively studied in the literature. Tests for compressive strength and flexural strength were conducted to characterize the mechanical properties of the UHPC mixtures. A Life Cycle Assessment (LCA) was conducted to quantify the environmental impacts of the different mixtures. Cement-efficiency and Environmental efficiency indexes were calculated to assess the potential of the UHPC mixtures.

2 MATERIALS AND METHODS

2.1 Materials and Mix Design

The UHPC mixtures used in the study were designed using the following powder materials: Portland Cement CP V, silica fume, quartz powder, quartz sand. A combination of polycarboxylate superplasticizer and viscosity modifier was used to improve the rheological properties of the mix. A reference mix was produced and then A 60% replacement rate was chosen to maximize the reduction in cement content while maintaining acceptable mechanical properties. The mixtures are presented in Table 1.

Table 1 Mix design of the concrete mixtures

Mixture	Cement (kg/m^3)	RHA (kg/m^3)	SF (kg/m^3)	QP (kg/m^3)	QS (kg/m^3)	Gravel	w/b	SP
UHPC	900	-	189	225	887	-	0.20	6%
LC-UHPC	360	540	189	225	698	-	0.20	6%

2.2 Mechanical properties

Compressive strength and Flexural Strength tests were carried at 28 days of age following the procedures established by EN 196 [14]. For compressive strength, 6 specimens of dimensions 4x4x4 cm were produced and tested for each mixture on an EMIC universal testing machine at a loading rate of 2400 N/s with a 3000 kN capacity load cell. For Flexural Strength tests, 3 prismatic specimens of dimensions 4x4x16 cm were produced and tested at a load rate of 50 N/s.

2.3 Life Cycle Assessment

The Life Cycle Assessment (LCA) was carried out following the procedures of ISO 14040 [15] and ISO 14044 [16]. The LCA was conducted in four steps: i) goal and scope definition; ii) life cycle inventory (LCI); iii) life cycle impact assessment (LCIA); iv) interpretation of results. The OpenLCA® software [17] for the analysis. A functional unity of 1 m³ of concrete was adopted for comparison between the different mixes of UHPC, CC and HSC.

2.3.1 Goal and scope definition

The goal of this LCA is to compare the CO_2 emissions of different concrete mixtures produced in Brazil. The scope of this study consists of the production of concrete mixtures from cradle to factory gate, i.e. from the extraction of raw materials to the mixing of concrete mixtures. The system boundary is presented in Fig. 1.

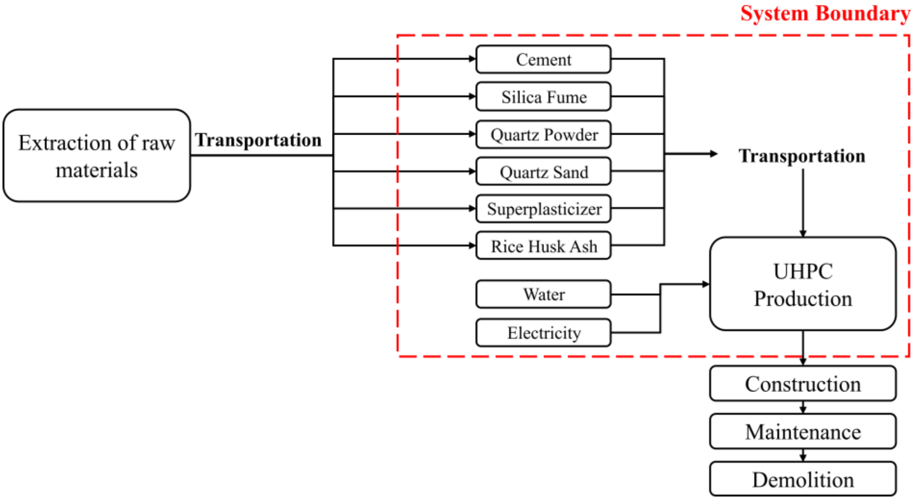

Fig. 1 System boundaries of the LCA

2.3.2 Life Cycle Inventory (LCI)

The LCI is a necessary step to quantify the inputs and outputs of the study [18]. The inputs consist of the raw materials needed for the concrete mixtures, the distances for transportation and the electricity needed for concrete mixing. Information on the production of cement, quartz powder, sand and water were extracted from the Ecoinvent database [19]. An allocation of 4.8% by mass of the impacts of ferrosilicon was considered for Silica Fume, following the recommendations of [20]. Inputs for the burning and milling of RHA followed the considerations of [21]. An environmental product declaration was utilized for the inputs of superplasticizer [22]. For the mixing of concrete, a value 2.7 kWh was considered as a standard for the production of concretes [23]. Table 2 presents the transportations distances used for the LCI.

Table 2 Transportation distances

Material	Origin	Destination	Distance (km)
Cement	Pedro Leopoldo, MG, Brazil	Belo Horizonte, MG, Brazil	35
RHA	Alegrete, RS, Brazil		2000
Silica Fume	Pirapora, MG, Brazil		350
Quartz Sand	Nova Lima, MG, Brazil		40
Quartz Powder	Analândia, SP, Brazil		600
Superplasticizer	Osasco, SP, Brazil		600

2.3.3 Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) was carried out using the Impact World+ [24]. This impact assessment methodology possesses 18 different impact categories for analysis. However, this study focused only on the "Climate Change, short term" impact assessment category, which refers to the CO_2 emissions of the system.

2.3.4 Interpretation

The interpretation phase of a life cycle assessment is the final step, where the outcomes from the inventory analysis and impact assessment are evaluated to draw conclusions and provide insights about the system. In this phase significant issues and contributors to environmental impacts are identified, ensuring findings are consistent with the proposed goal and scope of the study. Results for the UHPC and LC-UHPC mixtures were compared to conventional concrete [25] and high-strength concrete [26] available in literature.

2.4 Cement efficiency and environmental efficiency

Two parameters were calculated to evaluate the results of cement substitution: binder index (BI) for cement efficiency, and carbon efficiency (CI) for eco-efficiency. The binder index (Equation 1) is the relationship between the cement content of the mixture and the compressive strength, whereas the carbon index (Equation 2) considers the CO2 emissions of the UHPC mixtures. The indexes were compared to different concrete mixtures found in literature.

$$\mathrm{BI} = \frac{C}{f_c} \tag{1}$$

$$CI = \frac{CO_{2_{EQ}}}{f_c} \tag{2}$$

Where C is the cement content of the mixture in kg; f_c is the compressive strength of the mixture; and CO_2eq is the carbon footprint of UHPC in kgCO2eq.

3 RESULTS AND DISCUSSION

3.1 Mechanical Properties

The results for Compressive and Flexural Strengths at 28 days of age are presented in Fig. 1. Reductions of 10% in compressive strength and 4% in flexural strength were observed for the LC-UHPC mixture compared to the UHPC mixture. It's worth noting that this reduction in strength isn't notable, considering that 60% of the original cement content was replaced by the RHA. Moreover, the 134.9 MPa compressive strength is above what is considered the lower limit of compressive strength for UHPC, indicating that the high replacement of cement by RHA is a viable option to produce greener UHPCs.

Similar replacement rates of 60% of cement by RHA were not found in literature. It's usual to find studies regarding the replacement of cement by RHA in replacement rates between 10% [27] and 50% [13]. However, it was possible to find similarities from the existing research in literature. Comparisons between the LC-UHPC and other UHPC mixtures with RHA are presented in **Erro! Fonte de referência não encontrada.**

The small reduction in compressive strength of the LC-UHPC can be explained by both the pozzolanic and filler effects caused by the RHA. The cement reduction is compensated by the filler effect to the fineness and high surface area of the RHA [28], as well as the formation of secondary C-S-H due to the high amount of amorphous SiO_2 of the material [13].

Additionally, the high porosity of RHA gives the material the capability of absorbing part of the available water to release it gradually during cement hydration. Although the 28-day strength of LC-UHPC is slightly lower than that of the reference UHPC, the pozzolanic activity of RHA may lead to further strength gains at later ages [27,28].

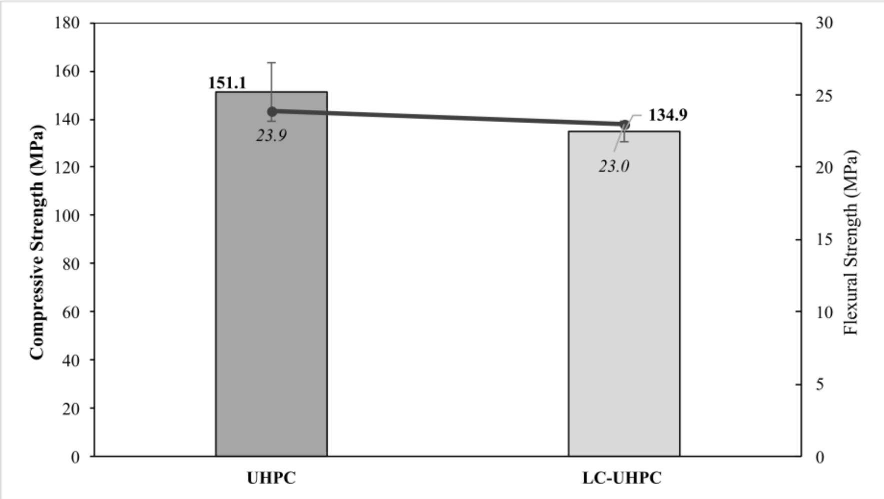

Fig. 2 Compressive strength and Flexural Strength of the concrete mixtures

3.2 LCA

The LCA was performed to quantify the environmental impacts of the production of 1 m³ of UHPC and LC-UHPC. For this research the Climate change, short term environmental impact category was studied. The CO_2 emissions of the UHPC and LC-UHPC are presented for each component. The CO_2 emissions, categorized as 'Climate change, long term,' are shown in Fig. 3Fig. 3. A reduction of 48% of CO_2 emissions is observed for the LC-UHPC mixture in relation to the reference UHPC mixture. Table 3 presents the results divided by their different materials. As expected, cement is the main contributor to the CO_2 emissions of UHPC. The 60% reduction of cement by replacement for RHA proved a viable option for the reduction of the environmental impacts of LC-UHPC.

The use of RHA contributes to 4.05% of the CO_2 emissions for the LC-UHPC, with transportation being the main contributor to the results due to the high distance presented in Table 2. The use of more locally available materials could mitigate the transportation impact and further reduce the CO_2 emissions for LC-UHPC.

Regarding the impacts of UHPC and LC-UHPC in comparison to conventional and high-strength concretes, results are shown in Fig. 3. The reduction of cement content made possible to produce greener UHPCs, with CO_2 emissions closer to those of CC and HSC.

Table 3 CO_2 emissions per material

Material	UHPC (kgCO2eq)	Contribution (%)	LC-UHPC (kgCO2eq)	Contribution (%)
Cement	758.81	81,47	302.32	62.39
Superplasticizer	53.74	5.79	53.74	11.09
Silica Fume	49.03	5.29	49.03	10.12
Quartz Sand	43.59	4.70	43.59	7.08
Quartz Powder	25.27	2.72	25.27	5.22
Water	0.04	0.00	0.04	0.01
Electricity	0.22	0.02	0.22	0.05
RHA	0	0	19.61	4.05

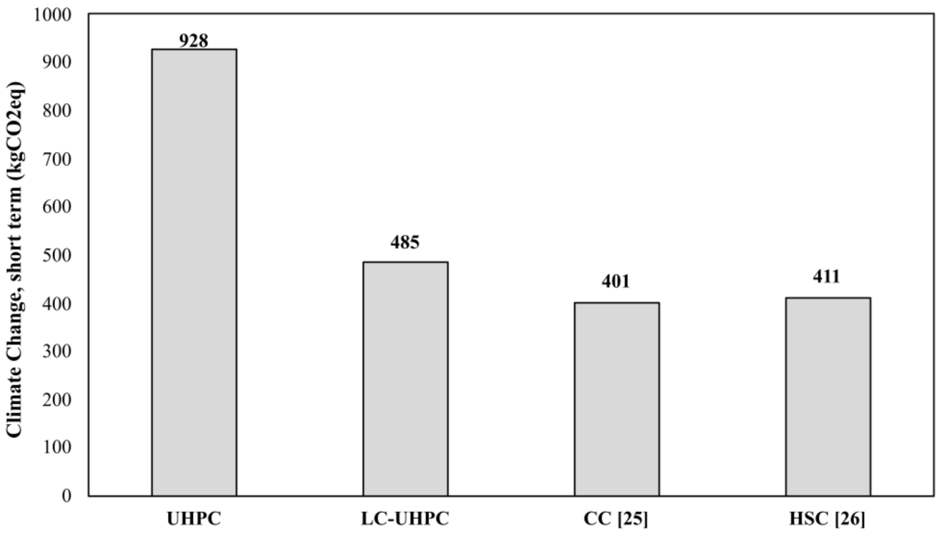

Fig. 3 CO_2 emissions of UHPC, LC-UHPC, CC [25] and HSC [26] mixtures

3.3 Cement efficiency and environmental efficiency

Binder index and carbon index were calculated to assess the cement and environmental efficiencies. These indexes are useful for comparing the results of UHPC and LC-UHPC to CC and HSC, accounting for the gains in compressive strength. The results are presented in Table 4. The calculated BI and CI for UHPC were 6.0 kg/m³/MPa and 6.1 kgCO2/m³/MPa, respectively. The results are smaller than the values for HSC (fc = 65 MPa), but the compressive strength is more than two times higher. The results are similar to the findings of [29,30]. Despite the higher cement content, less amount of cement is needed for 1 MPa in relation to CC and HSC. The BI and CI values for the LC-UHPC are 2.7 and 3.6, respectively, while the LC-UHPC is two times stronger than the HSC and almost four times stronger than the CC. The assessment of BI and CI indexes is essential for a better understanding of the sustainable potential of UHPCs when compared to more traditional concretes.

Table 4 Cement efficiency and carbon efficiency

Mixture	Cement content (kg)	Compressive Strength (MPa)	BI (kg/m³MPa)	CI (kgCO2/m³/MPa)
UHPC	900	151.1	6.0	6.1
LC-UHPC	360	134.9	2.7	3.6
CC [25]	425	35.0	12	11.5
HSC [26]	420	65.0	6.5	6.3

4 CONCLUSIONS

This study set out to evaluate the mechanical properties and environmental impacts of low cement UHPC produced with RHA as replacement of cement by 60%. Results showed that, despite a small reduction in compressive and flexural strength, it is possible to produce UHPCs with high cement replacement rates using RHA. In this case, RHA proved helpful for providing pozzolanic and filler effects, helping the strength development of the LC-UHPC.

Results from the LCA helped to assess the CO_2 emissions of the LC-UHPC and how it performs compared to conventional and high strength concretes. The energy and transportation distance required for RHA were not significant enough to make its use in LC-UHPC unfeasible in terms of CO_2 emissions.

The binder and carbon indices of UHPC and LC-UHPC highlight the high efficiency of the materials in comparison to conventional and high strength concretes. Optimizing UHPCs and LC-UHPCs to reduce cement consumption can lead to broader utilization of these materials in the future.

The findings of this study suggest that LC-UHPC has the potential to contribute to more sustainable infrastructure projects, particularly in applications where high-performance materials are required, such as bridge construction and high-rise buildings.

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