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Comparing conventional concrete to high performance concrete through life cycle assessment

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Abstract

In this study, conventional concrete is compared to high performance concrete in terms of environmental performance. The Open LCA software along with the Ecoinvent database 3.1 and data from a literature review were used. The ReCiPe life cycle impact assessment methodology was applied. Results show better environmental performance for high performance concrete. Regarding climate change and water depletion results, conventional concrete turned out to have almost twice the impact of high performance concrete, while for the fossil depletion and human toxicity indicators results were even higher. In addition, it must be noted that high performance concrete also results in benefits regarding dematerialization since it is needed 0.654 m^3 less than in the conventional concrete case for the same function. Nevertheless, further analysis should be conducted using primary data.

Keywords: life cycle assessment, cement-based materials, sustainable construction.

Comparando o concreto convencional com o concreto de alto desempenho através da avaliação do ciclo de vida

Resumo

Neste estudo, o concreto convencional é comparado ao concreto de alto desempenho em termos de desempenho ambiental. Utilizou-se o software Open LCA, a base de dados Ecoinvent 3.1 e dados de revisão de literatura. Aplicou-se a metodologia de avaliação de impacto do ciclo de vida do ReCiPe. Os resultados mostram melhor desempenho ambiental para concretos de alto desempenho. Em relação aos resultados de mudanças climáticas e esgotamento de água, o concreto convencional apresentou quase o dobro do impacto do concreto de alto desempenho, enquanto aos indicadores de depleção fóssil e toxicidade humana os resultados foram ainda maiores. Além disso, deve-se ressaltar que o concreto de alto desempenho também resulta em benefícios em relação à desmaterialização, uma vez que são necessários 0,654 m^3 a menos do que no concreto convencional para a mesma função. No entanto, análises adicionais devem ser realizadas usando dados primários.

Palavras-chave: avaliação do ciclo de vida, materiais à base de cimento, construção sustentável.

1. Introduction

A life cycle assessment (LCA) is the assessment of the environmental impact of a given product throughout its lifespan (International Organization for Standardization, 2006a, 2006b). LCA has been used in the building sector since 1990 (Fava, 2006), and it is now a widely used methodology (Häfliger et al., 2017).

LCA compares different solutions that will provide the same function and identifies opportunities to improve the environmental performance of products and services in various phases of their life cycle. The term “life cycle” refers to the idea that for a fair, holistic assessment the raw material production, manufacture, distribution, use and disposal need to be assessed.

LCA is essential in order to compare the environmental performance of concrete mixes. Usually, LCA are implemented for 1 m^3 of concrete when comparing concrete mixes. In this study, a LCA is carried out considering a structural element. This is a step further on the life cycle of concrete which include raw materials extraction, concrete production, concrete use and end of life for a structural element.

The objective of this study is to compare conventional concrete to high performance concrete (HPC) - which is a relatively new type of concrete with compressive strength of 50 MPa or more and a set of standards above those of the most common concretes (Malier, 2018). This is for a specific structural element with a specific load. These results should be complemented with a life cost analysis in order to assess the viability of the implementation of high performance concrete towards sustainable development.

2. Materials and Methods

2.1 Literature review

A literature review was conducted in order to contextualize life cycle assessment for concrete and identify data for the study (Rowley; Slack, 2004). The literature review includes relevant material published in scientific journals, books and conference proceedings from bibliographic databases such as Google Scholar, Web of Science and Scopus which are the largest abstract and citation databases. Papers and bibliography were selected according to their relevance. Four LCA studies on conventional concrete, high performance concrete, ultra-high performance concrete, frost-resistance concrete and admixtures such as superplasticizers were studied in detail.

2.2 Life cycle assessment

The Open LCA version 1.4 was used along with the Ecoinvent database 3.1 and data from the literature review. The four phases of LCA were performed according to the ISO 14040 standard. In addition, a comparison between the study and reviewed papers was made.

The goal of the present LCA is to compare the environmental performance of conventional concrete and high performance concrete for a 3 m tall square section concrete column (structural element) supporting a 18750 KN load. High performance concrete demands less materials for a single structural element; however, it uses admixtures (superplasticizers) in its composition in order to increase compressive strengths, workability and to maintain a low water/cement ratios (Yuan et al., 2023). As a result, using these high performance additives may imply greater environmental impacts.

The system boundaries comprise life cycle assessment for processes from raw material extraction to placing concrete into a clean truck, all these processes occurring inside the concrete plant. The use phase and end of life phase of the product are excluded in this study since this is a cradle to gate LCA. The chosen functional unit is a 3 m tall square section concrete building column (structural element) supporting a 18750 KN load. Table 1 shows properties, dimensions and volume for two concrete options. The two concrete options, even if they do not have exactly the same dimensions, correspond to the functional unit and can therefore be compared.

Table 1. Properties, dimensions and volume for two concrete options.

Concrete	Compressive strength (MPa)	Column section (m^2)	Concrete volume (m^3)
Conventional concrete	35	0,535714	1,607
HPC	59	0,317797	0,953

Source: Author, 2024.

Four midpoints indicators were selected: climate change, fossil depletion, human toxicity and water depletion. These indicators will be explained along with their respective units.

Both product systems consist of two processes: “concrete production” and “placing concrete into truck” (see Figure 1, Figure 2 and Figure 3). In order to create the product system, the Ecoinvent version 3.1 database was imported to the Open LCA software. For the product system some of the flows and processes were used directly from the Ecoinvent version 3.1 database, as in the case of the "concrete production" process while other flows and processes had to be created and fed by literature data, such as "placing into concrete truck" process. In the case of the "concrete production" process even though the process was available in the Ecoinvent version 3.1 database, the amounts were adjusted to fit this study.

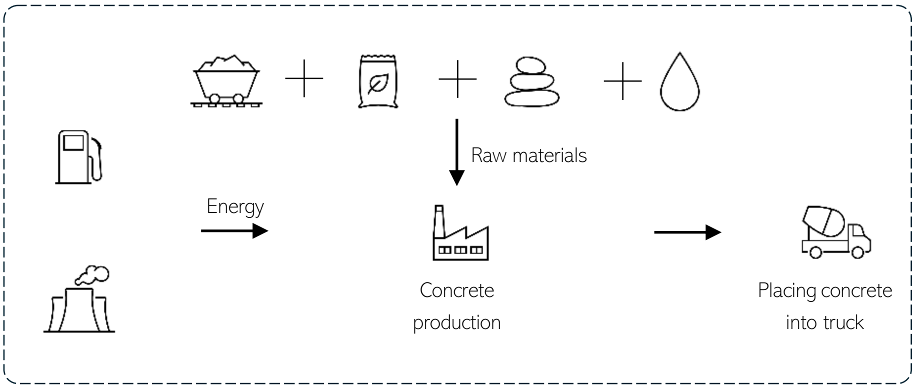


Figure 1. Graphic representation of the product system. Source: Author, 204.

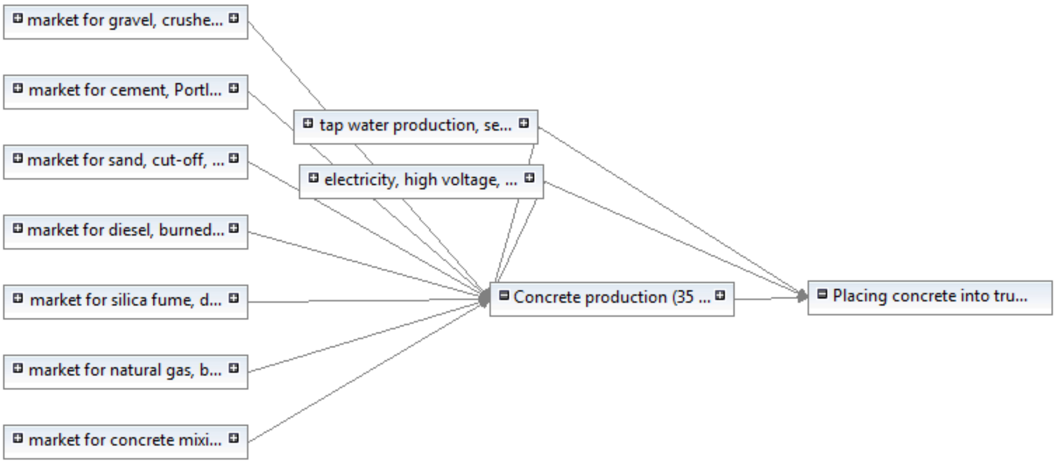


Figure 2. Open LCA Product system - Conventional concrete (35 MPa). Source: Open LCA software.

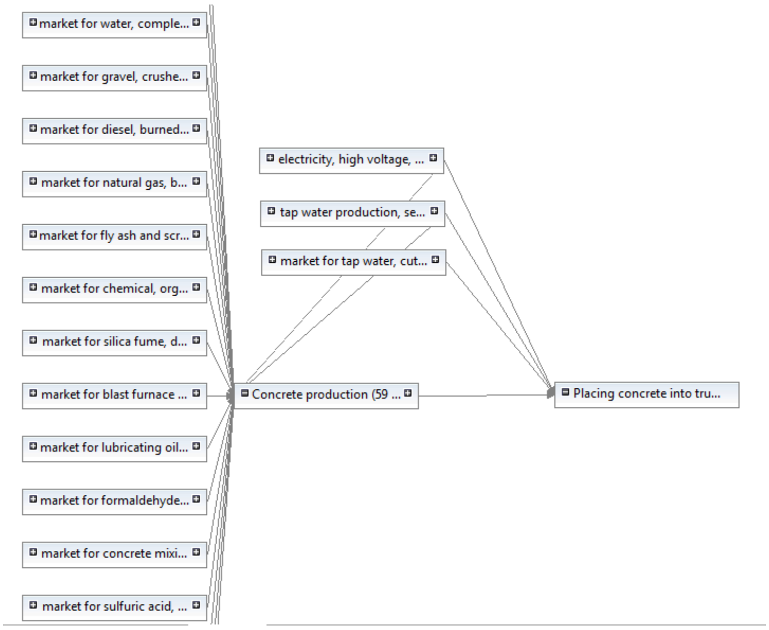


Figure 3. Open LCA High performance concrete (59 MPa). Source: Open LCA software.

Concrete has as components: aggregates, water, cement and chemical admixtures. During the concrete production process, the different components come together to form a uniform mass which can be molded into different shapes. Conventional concrete comprises compression strengths under 50 MPa while high performance concrete is defined by Lafarge (2013) as concrete with compressive strength greater than 50 MPa. High performance concrete composition includes superplasticizer admixtures which increases its workability and keeps low water/cement ratios.

Inventory data for conventional concrete (35 MPa) and high performance concrete (59 MPa) is presented in Table 8 and Table 9 respectively. For conventional concrete (35 MPa), inventory data was compiled from the PCA Environmental Life Cycle Inventory of portland cement concrete in its majority and also from the Ecoinvent database 3.1. For conventional concrete (59 MPa), inventory data was compiled from the PCA Environmental Life Cycle Inventory of Portland cement concrete, Chapter 17 from Design and Control of Concrete Mixtures engineering bulletin (Kosmatka et al., 2003), and Ecoinvent database 3.1.

The chosen life cycle impact assessment method for the study is ReCiPe Midpoint (E). ReCiPe integrates midpoint and endpoint approach. It has regional validity for Europe, Global for Climate change, Ozone layer depletion and resources and time horizon of 20 years, 100 years or indefinite, depending on the cultural perspective (JRC European Commission, 2010). Converting the extensive compilation of Life Cycle Inventory results into a handful of indicator scores is the main goal of the ReCiPe approach. The relative severity of an environmental impact category is expressed by these indicator ratings. ReCiPe bases its modeling on an environmental mechanism, which may be seen as a set of interrelated impacts that cumulatively have the potential to cause a specific amount of harm to, say, ecosystems or human health. In ReCiPe the indicators are determined at two levels:

1. Eighteen midpoint indicators
2. Three endpoint indicators

A midpoint indicator can be defined as a parameter in a cause-effect chain or network (environmental mechanism) for a particular impact category that is between the inventory data and the category endpoints. Endpoint characterization factors (or indicators) are calculated to reflect differences between stressors at an endpoint in a cause-effect chain and may be of direct relevance to society's understanding of the final effect. Both midpoint and endpoint methods requires building a proper inventory and hence using an impact method to transform emissions to potential environmental impact. Endpoint characterization is more complex and relatively more uncertain and midpoint results being more robust and certain. The choice between midpoints and endpoints is mainly driven by the goal of the LCA and who is the LCA for. For this study midpoint methodology was chosen since the study correspond to research purposes.

Each method (midpoint, endpoint) contains factors according to the three cultural perspectives:

- Individualist: short term, optimism that technology can avoid many problems in future. Considers the proven environmental impacts.
- Hierarchist: consensus model, as often encountered in scientific models.
- Egalitarian: long term based on precautionary principle thinking. Considers all environmental impacts proven or not.

These perspectives represent a set of choices on issues like time or expectations that proper management or future technology development can avoid future damages (Characterisation – ReCiPe, n.d.). For this study Egalitarian (E) cultural perspective was chosen.

For the present LCA the next four impact categories were selected as they are considered to be relevant for concrete production LCIA. Cementitious materials industry generates significant environmental impacts in terms of CO_2 emissions and energy consumption for this reason these impacts must be properly quantified and assessed. Water consumption is an environmental impact that has been relatively ignored in the production of cementitious materials either because of lack of data or because they are considered to be insignificant. However nowadays due to the water scarcity problems, this impact has gained great relevance and is being assessed in a more meticulous way. As for human toxicity, in this study is considered very important aspect because it directly affects people.

Equivalent carbon dioxide (CO_2 eq) is a functionally equivalent amount or concentration of CO_2 as the reference to measures how much global warming a given type and amount of greenhouse gas may cause. The carbon dioxide equivalency for a gas is obtained by multiplying the mass and the Global Warming Potential (GWP) of the gas.

Kilogram(s) of oil equivalent is a normalised unit of energy equivalent to the approximate amount of energy that can be extracted from one kilogram of crude oil. This unit has an assigned net calorific value of 41 868 kilojoules/kg and may be used to compare the energy from different sources.

$C_6H_4Cl_2$ is the formula for the chemical compound 1,4-dichlorobenzene. Humans who inhale 1,4-dichlorobenzene over a brief period of time experience irritation of their eyes, throat, and skin. Humans who breathe in 1,4-dichlorobenzene over an extended period of time may experience consequences on their liver, skin, or central nervous system (CNS). EPA has classified 1,4-dichlorobenzene as a Group C, possible human carcinogen. For each toxic substance human toxicity potentials are expressed using the reference unit, kg 1,4-dichlorobenzene (1,4-DB) equivalent.

For the water depletion a midpoint indicator of cubic meter (m^3) expresses the total amount of water used and considers water flows such as: water from rivers and lakes, water from wells and water from unspecified natural origin. This indicator consist of summation of all different water flows.

The four impact categories correspond to ReCiPe midpoint methodology.

3. Results and Discussion

3.1 Literature review

Four LCA studies on conventional concrete, high performance concrete, ultra-high performance concrete, frost-resistance concrete and admixtures such as superplasticizers are presented.

3.1.1 Life cycle assessment of concrete (Sjunnesson, 2005)

3.1.1.1 Goal and scope

The study focuses particularly on the superplasticizers used as admixtures and is conducted for two types of concrete: ordinary and frost-resistant concrete. Since the sort of structure for which the concrete is utilized is not specified, the utilization phase is not covered in this study. The functional unit is 1 m^3 of concrete.

3.1.1.2 Inventory data

The composition of the two types of concrete used in this study is presented in Table 2.

Table 2. Concrete proportions.

Formulation	**Ordinary concrete (C 20/25)**		**Frost-resistance concrete (35/45)**	
	kg/m^3	%	kg/m^3	%
Cement	295	13	434	18
Macadam	749	32	951	40
Natural gravel	1093	47	828	35
Superplasticizer (Peramin F)	1,51	0,06	0,95	0,04
Air-entraining admixdure (Peramin HPA)	-	-	3,3	0,1
Total amount of water	202	8,6	167	7

Source: (Jeannette Sjunnesson, 2005).

Energy demands and emissions for cement, aggregates, admixtures, concrete production are presented in Table 3.

Table 3. Energy demand and emissions to air.

Parameters		**1 kg cement**	**1 kg macadam**	**1 kg gravel**	**1 kg superplasticizer**	**1 m^3 concrete (production)**	**1 m^3 concrete (demolition)**
Energy							
Coal	MJ	1,9	-	9,60E-05	1,7	-	-
Coke	MJ	0,51	-	1,00E-03	-	-	-
Crude oil	MJ	-	-	-	3,2	15	-
Natural gas		-	-	-	8,2	-	-
Diesel	MJ	0,03	0,02	1,10E-05	-	-	0,007
Car tires	MJ	0,42	-	2,20E-05	-	-	-
Bone meal	MJ	0,01	-	1,10E-04	-	-	-
Electricity	MJ	0,48	0,03	2,40E-03	2,9	33	-
Emissions to air							
CO_2	kg	0,71	1,6 g	0,07 g	0,69 kg	1,5 kg	0,54 g
CO	mg	2,7	0,81 mg	0,07 mg	2,1 g	0,86 g	0,09 mg
NO_x	g	0,7	14 mg	0,6 mg	3,5 g	2,3 g	5,3 mg
SO_x	g	0,09	0,78 mg	0,05 mg	6,6 g	3,3 g	0,28 mg
CH_4	g	2,6	1,7 mg	0,38 microg	1,2 g	1,7 g	0,01 mg
HC	mg	1,3	0,9 mg	0,04 mg	2,2 g	0,32 g	0,31 mg

Note: CO_2 (carbon dioxide); CO (carbon monoxide); NO_x (nitrogen oxides); SO_x (sulfur oxides); CH_4 (methane); HC (hydrocarbon). Source: Author, 2024.

3.1.1.3 Life cycle impact assessment and results

3.1.1.3.1 Global warming Potential

The primary source of the global warming potential (GWP) in the concrete life cycle is the raw material production. It contributes about 85% of the GWP overall. Because of the cement factory's calcination process, the manufacture of cement generates the most greenhouse gas emissions among raw materials. The calcination process accounts for about 69% of the factory's CO_2 emissions, with fossil fuel use accounting for the remaining 31%.

3.1.1.3.2 Energy consumption

Cement production has the highest energy demand both as electricity and fossil fuels. Superplasticizers use 2% of both electricity and fossil fuel in ordinary concrete and 4% of electricity and 3% fossil fuel in frost-resistant concrete.

3.1.1.3.3 Toxicity

In a worst-case scenario, the study indicates that roughly 15-25% of sulphonated naphthalene polymers (SNP), lignosulphonate, and polycarboxylates, and 30-60% of sulphonated melamine polymers (SMP), were leached. This may sound like a lot, but further testing revealed that superplasticizers are only responsible for a portion of the overall amount of leached organic chemicals; the remainder originates from other goods like adhesives and coatings.

3.1.1.3.4 Conclusions

The environmental impact of frost-resistant concrete is between 24-41 % higher than that of ordinary concrete due to its higher content of cement. Superplasticizers contribute with approximately 0.4-10.4 % of the total environmental impact of concrete, the least to the global warming potential (GWP) and the most to the photochemical ozone creation potential.

3.1.2 Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges (Habert et al., 2012)

3.1.2.1 Goal and scope

This study evaluates the environmental consequences of using high performance concrete instead of ordinary concrete for a bridge. In this study, the chosen functional unit is the crossing of a four-lane divided highway with a two-lane road over a one-hundred year time period.

3.1.2.2 Inventory data

The components for different concretes are presented in Table 2.

Table 2. Concrete mix designs used during the life cycle of both bridges solutions.

Concrete type	**Unit**	**Cement (kg)**	**Limestone filler (kg)**	**Admixture (kg)**	**Water (kg)**	**Sand (kg)**	**Round gravel (kg)**	**Crushed gravel (kg)**	**Bitumen (kg)**	**Heating**
Low strength concrete	m^3	225	75	1,66	150	740	380	690	-	-
Foundation concrete	m^3	385	-	2,7	185	740	380	690	-	-
Deck concrete	m^3	290	125	2,9	170	660	300	760	-	-
Pylon concrete	m^3	420	-	2,9	155	650	400	615	-	-
C60 precast concrete	m^3	450	-	6,75	177	810	910	-	-	250 KWh
C80 concrete	m^3	425	-	9	133	790	1050	-	-	-
Repair mortar	m^3	380	-	-	-	2380	-	-	-	-
Precast concrete	m^3	190	60	1,66	125	740	380	690	-	250 KWh
Pavement	T	-	-	-	-	-	944	-	55,4	-
Bitumen sealing	m^2	-	-	-	-	-	-	69,88	4,98	-
Sheet asphalt	kg	-	-	-	-	0,66	-	-	0,08	17,35 MJ

Source: Habert et al. (2012).

3.1.2.3 Life cycle impact assessment and results

The findings indicate that, overall, using high performance concrete instead of ordinary concrete for bridge construction is more environmentally beneficial.

3.1.2.4 Conclusions

The present study shows that choosing a high performance bridge construction solution to cross a four lane divided highway with a two-lane road is always more environmentally friendly than a traditional concrete bridge solution, regardless of the observed environmental impact and the geographic context.

3.1.3 Life cycle assessment of UHPC bridge constructions: Sherbrooke footbridge, Kassel Gärtnerplatz footbridge and Wapello road bridge (Stengel et al., 2008)

3.1.3.1 Goal and scope

The paper presents the results of life cycle assessments (LCA) performed for three bridges in which UHPC was an essential part of the structure. The results comprise only the assessment of the materials used for the bridges including the raw materials and the infrastructure necessary for production. Heat treatment of UHPC, transport to the construction, maintenance as well as disposal of the bridges has not yet been considered. The functional unit is one section of each bridge without foundation. Due to lack of information, the bridge railing is not considered in this study.

3.1.3.2 Inventory data

Materials used and origin if materials data are presented in (Table 5). The life cycle inventory analysis and impact assessment were carried out using SimaPro version 7.1 software. The data required to construct a product were retrieved from the econinvent database as well as from our own data compilation.

Table 3. Concrete composition for each bridge.

	Unit	**Sherbrooke**	**Gärtnerplatz**	**Wapello**
Ductal CS 1000 premix	-	-	-	2194
Cement	kg/m^3	710	733	-
Silica sand content	kg/m^3	1010	1091	-
Quartz powder	kg/m^3	210	183	-
Silica fume	kg/m^3	230	230	-
Water	kg/m^3	200	161	131
Steel fiber	kg/m^3	190	192	156
Superplasticizer	kg/m^3	19 l/m^3	30	30

Source: Stengel et al. (2008).

3.1.3.3 Life cycle impact assessment and results

The ecological effects of global warming (GWP100), depletion of the stratospheric ozone (ODP), photo-oxidant formation (POCP), acidification (AP) and eutrophication (NP) were adopted as impact category indicators.

3.1.3.4 Conclusions

The results show that UHPC used in the Sherbrooke footbridge and the Gärtnerplatz footbridges causes approximately 60 to 85% of the environmental impact. The Wapello road bridge has a somewhat smaller contribution from UHPC to the environmental impact, ranging from 44 to 74%. As well as UHPC, in particular normal concrete in the bridge deck, the steel reinforcement of the bridge deck and the prestressing of the UHPC contribute appreciably to the effect on the environment.

3.1.4 Methodology of life-cycle assessment or RC structures using high performance concrete (Fiala et al., 2013)

3.1.4.1 Goal and scope

A LCA approach from cradle to the gate is presented in environmental analysis of three alternatives of experimentally verified subtle columns. Relevant LCA is based on local environmental data collected within the inventory phase of the LCA procedure. Environmental assessment was evaluated for three selected alternatives of subtle columns. The environmental analysis covers transport of the raw material to the concrete plant and production of prefabricated elements in the plant.

3.1.4.2 Inventory data

Aggregated impact data of construction life phase is presented in (Table 6).

Table 6. Balance of input data of construction life phase.

	Unit	**V1 column (155 MPa) HPC SL + R**	**V2 column HPC SL**	**V3 column C30/37 + R**
Ordinary concrete C30/37	m3	0	0	0,0492
High performance concrete HPC SL	m3	0,0492	0,05	0
Cement CEM II 32.5 R	MJ	0	0	17,2
Cement CEM I 42.5 R	kg	33,4	34	0
Sand | gravel	kg	47,2	48	51,6
Crushed gravel	kg	0	0	38
Silica fume	kg	8,6	8,8	0
Micro milled sand	kg	16	16,3	2,5
Steel fibers	kg	3,9	4	0
Admixture (PCE) superplasticizer	kg	1,4	1,5	0,2
Water	kg	8,4	8,5	9,6
Reinforcing bars R 10505	kg	6,5	0	6,5
Freight traffic	tkm	23,1	23,5	8,5

Source: Fiala et al. (2013).

3.1.4.3 Life cycle impact assessment and results

The life cycle impact assessment results are presented in Table 7 for the different impact categories.

Table 7. Aggregated impact data of construction life phase.

	Unit	**V1 column HPC SL + R**	**V2 column HPC SL**	**V3 column C30/37 + R**
Consumption of primary raw materials	kg	178	169	144
Water consumption	m^3	0,1	0,1	0,1
Primary energy consumption	MJ	579	409	313
Global warming potencial	kg	64	49	32
Acidification Potencial	g	298	200	151
Photochemical ozone creation potencial	g	12	8	6
F	kN	749.8	1033.0	648.9
Primary energy consumption EE	MJ/column	579	409	313
EE/F	MJ/kN	0.772	0.396	0.482
Global warming potencial GWP	kg CO_2 equiv/column	64	49	32
GWP/F	kg CO_2 equiv/kN	0.085	0.047	0.049

Source: Fiala et al. (2013).

3.1.4.4 Conclusions

The first solution labeled V1 presents higher impact assessment results. It can be seen that major part of these impacts comes from steel fibers used in high performance concrete composition, cement and admixtures also increase environmental impacts for high performance concrete.

3.2 Conventional concrete (35 Mpa) vs High performance concrete

Table 8 and Table 9 gather the life cycle inventory for conventional concrete and high performance concrete respectively.

Table 8. Conventional concrete (35 MPa) data inventory.

Concrete production process data inventory			**Placing concrete into truck process data inventory**		
Flow	Amount	Unit	Flow	Amount	Unit
Inputs			*Inputs*		
Water (miscellaneous)	129	kg	Concrete (35 Mpa)	1	m3
Energy (plant operation)			Water	69	kg
Diesel fuel	0,191	GJ	Energy	0,02964	GJ
Natural gas	0,042	GJ	Water (truck wash)	150	kg
Electricity	0,014	GJ	Energy (truck wash)	0,03705	GJ
Material transportation	0,131	GJ			
Concrete mix					
Water	141	kg			
Cement	284,75	kg			

	Fly ash	50,25	kg			
	Gravel	1200	kg			
	Sand	710	kg			
	Outputs			*Outputs*		
	Waste water	83,85	kg	Waste water	51,75	kg
Plant operation	Emissions		kg	Emissions		kg
	Particulate matter	0,101	kg	Particulate matter	0,01212	kg
	CO_2	14,2	kg	CO_2	1,704	kg
	SO_2	0,083	kg	SO_2	0,00996	kg
	NO_x	0,014	kg	NO_x	0,00168	kg
	VOC	0,0003	kg	VOC	0,000036	kg
	CO	0,004	kg	CO	0,00048	kg
	CH_4	no data	kg	CH_4	no data	kg
Material transportation	Emissions		kg	Emissions (because of truck wash)		
	Particulate matter	0,012	kg	Particulate matter	0,01515	kg
	CO_2	9,3	kg	CO_2	2,13	kg
	SO_2	0,015	kg	SO_2	0,01245	kg
	NO_x	0,086	kg	NO_x	0,0021	kg
	VOC	0,015	kg	VOC	0,000045	kg
	CO	0,085	kg	CO	0,0006	kg
	CH_4	0,003	kg	CH_4	no data	kg
	Waste water	35	kg	Waste water (because of truck wash)	142,5	kg
	Concrete (35 Mpa)	1	m^3	Concrete (35 Mpa)	1	m^3

The life cycle inventory results are presented in Table including different activities and materials for concrete production.

Table 9. High Performance Concrete (59 Mpa) data inventory.

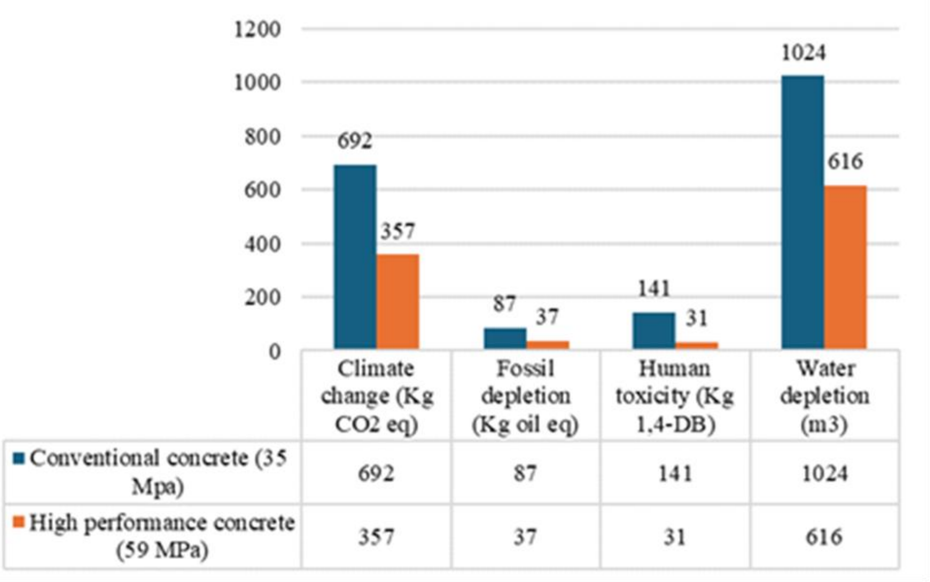
Concrete production process data inventory			**Placing concrete into truck process data inventory**		
Flow	Amount	Unit	Flow	Amount	Unit
Inputs			*Inputs*		
Water (miscellaneous)	129	kg	Concrete (59 Mpa)	1	m^3
Energy	0,247	GJ	Water	69	kg
Transportation	0,131	GJ	Energy	0,02964	GJ/metric ton
Water	151	kg	Energy (truck wash)	0,03705	GJ/metric ton

Cement	311	kg	Water (truck wash)	150	kg
Fly ash	31	kg			
Slag	47	kg			
Silica fume	16	kg			
Gravel	1068	kg			
Sand	676	kg			
Plasticizer					
Synthetic rubber	0,00733	kg			
Water completely softened	1,86	kg			
Tap water	0,267951	kg			
Sulfuric acid	0,454	kg			
Lubricating oil	0,0122	kg			
Sodium hidroxide	0,374	kg			
Chemical organic	0,456	kg			
Steel low alloyed	0,0244	kg			
Formaldehyde	0,105	kg			
Outputs			*Outputs*		
Waste water	83,85	kg	Waste water	51,75	kg
Emissions		kg	Emissions		kg
Particulate matter	0,101	kg	Particulate matter	0,01212	kg
CO_2	14.2	kg	CO_2	1,704	kg
SO_2	0,083	kg	SO_2	0,00996	kg
NO_x	0,014	kg	NO_x	0,00168	kg
VOC	0,0003	kg	VOC	0,000036	kg
CO	0,004	kg	CO	0,00048	kg
CH_4	no data	kg	CH_4	no data	kg
Emissions		kg	Emissions (because of truck wash)		
Particulate matter	0,012	kg	Particulate matter	0,01515	kg
CO_2	9,3	kg	CO_2	2,13	kg
SO_2	0,015	kg	SO_2	0,01245	kg
NO_x	0,086	kg	NO_x	0,0021	kg
VOC	0,015	kg	VOC	0,000045	kg
CO	0,085	kg	CO	0,0006	kg
CH_4	0,003	kg	CH_4	no data	kg
Waste water	35	kg	Waste water (because of truck wash)	142,5	kg
Concrete (59 Mpa)	1	m^3	Concrete (59 Mpa)	1	m^3

Source: Author, 2024.

Figure 4 shows a comparison of the two concrete solutions for the different impact categories. For the four selected impact categories the conventional concrete (35 MPa) resulted in greater environmental impacts than high performance concrete (59 MPa). However, further analysis should be conducted using primary data.

Compared to the "Reducing environmental impact by increasing the strength of concrete" study by Habert et al. (2012), the result of this study agrees that the use of concrete with high and ultra-high performance characteristics results in lower environmental impacts than conventional concrete. As for the "Methodology of life-cycle assessment or RC structures using high performance concrete" study by Fiala et al. (2013) this study concludes that the use of HPC results in higher environmental impact due to the use of steel fibers which is not the case of our study. It must be clarified that the comparison between the present study and others from literature is very difficult and not always possible since the functional unit, system boundaries, product composition and other aspects of the LCA are different. Carefully attention must be paid to the interpretation of the water depletion indicator which include water flows for all background processes.



	Climate change (Kg CO2 eq)	Fossil depletion (Kg oil eq)	Human toxicity (Kg 1,4-DB)	Water depletion (m3)
■ Conventional concrete (35 Mpa)	692	87	141	1024
■ High performance concrete (59 MPa)	357	37	31	616

Figure 4. Conventional concrete (35 Mpa) vs High performance concrete (59 Mpa) environmental impact results. Source: Author, 2024.

4. Conclusions

Results show better environmental performance for high performance concrete in all four studied indicators (climate change, fossil depletion, human toxicity and water depletion). In addition to better environmental performance, it must be noted that high performance concrete also results in benefits regarding dematerialization since it is needed less volume of high performance concrete than in the conventional concrete case for the same function. It can be said that using high performance concrete represents an opportunity to improve environmental performance in civil construction. Nevertheless, the effective application and quality of results of LCA are dependent on the availability of relevant input data obtained using a detailed inventory analysis, based on specific regional data sources.

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6. Authors' Contributions

Yazmin Lisbeth Mack-Vergara: research, conceptualization, writing of the article and publication.

7. Conflicts of Interest

No conflicts of interest.

8. Ethics Approval

Not applicable.

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