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LIFE CYCLE ASSESSMENT OF CARBON CONCRETE COMPOSITES: A CIRCULAR ECONOMY PATH BEYOND CLIMATE MITIGATION?

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Abstract. Sustainable construction and materials play an ever-important role to stay within our planetary boundaries. In support, innovative carbon concrete composites (CCC) promise significant raw material savings by integral design. We aim to illustrate current environmental hotspots and a feasible recycling scenario of CCC that meets circularity requirements. We modelled a cradle-to-grave life cycle assessment for two potential building structural applications (sandwich wall, ceiling reinforcement) made of CCC. We based our recycling scenario on previously conducted large-scale experiments. Results show a relative larger energy intensity and abiotic depletion of fossil fuels for variants of CCC but lower global warming. Yet, recycling is, second to embodied emissions of basic materials, the driving force of total environmental impacts. The presented recycling path (demolition, pyrolysis for carbon fabric, reuse in fiber fleece) offers less "green credentials" than steel.

Keywords: Carbon concrete composite, life cycle assessment, recycling.

1. Introduction

The European construction industry including buildings contributes to 9% in EU's GDP, but is also held accountable for roughly 90% of used mineral resources, 40% of energy consumption, and 35% carbon emissions [1]. To minimize negative effects on our planetary boundaries, a dedicated pathway to sustainable construction is key. An ever-increasing regulatory attention is paid to climate change and circular economy that could eventually improve Sustainable Development Goals #9 to #13. Circular economy, as synthesized by Potting et al. [1], allows to align environmental strategies along nine "Rs". Decision-makers are asking to what extend new building materials can help achieving these goals. They may offer options of considerable raw material savings ("R2 Reduce") by integral design ("R5 Refurbish"), remedial maintenance ("R0 Refuse") or closing material loops ("R8 Recycle").

In this study, carbon concrete composites (CCCs) are examined as type of textile reinforced concrete (TRC). CCC is understood as cement-based carbon fiber reinforced composites using a fine-grained concrete [2] and mesh-like textile reinforcements or carbon fiber rods as basic materials. In comparison to steel reinforced concrete (SRC), the use of high-performance carbon fibers offers a much wider "range of application specific properties" [3]. CCCs still need to showcase whether its application is environmentally, socially and financially viable [4] though seemingly functionally superior including beneficial raw material savings. Despite of over 20 years of intensive studies on CCC by two German collaborative research centers in Dresden and Aachen [5] and a succeeding joint research center "C^3 Carbon Concrete Composite" little is known about sustainability of CCC.

An initial scoping review revealed that pertinent literature on CCC is dominated by structural and mechanical tests. There is only a few published work on sustainability assessments. Many cases refer to carbon fiber reinforced plastics (CFRPs) in other product contexts, e.g. automotive or railway. For example, Das [10] applied LCA for CFRP components in cars quantifying primary energy consumption (PE) and greenhouse gas emissions to show lightweight advantages. CFRP has also been studied for reinforcements of bridges and façades. Cadenazzi et al. [15] assessed five life cycle impact assessment (LCIA) indicators whereas Hájek et al. [8] calculated four, e.g. global warming (GW) and acidification (AP): CFRP performed better than SRC in both cases.

For CCC, Williams Portal et al. [9] examined reinforcement technologies, e.g. SRC and CCC, with cradle-to-gate LCA. CCC scored the lowest total environmental impact. Laiblová et al. [7] compared

Materials	Value*	Unit	Life cycle	Examined product	Source
Carbon concrete composites (CCC)	34-109	[kg CO_2eq/m^2]	A1-C3**	façade sandwich panels	[6]
	21.83	[kg CO_2eq/m^2]	A1-C3	façade element	[7]
	0.35***	[kg CO2eq/MPa]	A1-A3	façade element	[8]
Carbon fiber reinforced plastics (CFRP)	295.93	[kg CO2eq/m^3]	A1-A3	slab, case "CA1"	[9]
	345	[kg CO2eq/kg]	A1-A3	car component, "PAN SMC"	[10]
	30-52	[kg CO2eq/kg]	A1-A3	car component, various manuf.	[11]
CFRP rebar/strip	19.70	[kg CO2eq/kg]	A1-A3	rebar	[12]
Carbon fiber	17.43-34.39	[kg CO2eq/kg]	A1-A3	PAN carbon fiber	[13]
	24.20-31	[kg CO2eq/kg]	A1-A3	Lignin and PAN carbon fiber	[10]
	11.40	[kg CO2eq/kg]	A1-A3	PAN carbon fiber	[14]
Epoxy resin	5.25-8.25	[kg CO2eq/kg]	A1-A3	GaBi database, for DE/Europe	-
Steel reinforced concrete (SRC)	129	[kg CO_2eq/m^2]	A1-C3	façade sandwich panel	[6]
	26.33	[kg CO_2eq/m^2]	A1-C3	façade element	[7]
Concrete C25/30	197	[kg CO2eq/m^3]	A1-A3	German mix, cement 11.1%	EPD
	0.09	[kg CO2eq/kg]	A1-A3	~	EPD
Reinforcing steel	0.31	[kg CO2eq/kg]	A1-A3	girders for concrete slabs	EPD
	0.68	[kg CO2eq/kg]	A1-A3	reinforcement steel wire	EPD

* all indicator values are based on dimensions given in each study.
** "Life cycle" refers to examined life cycle stages using nomenclature of EN 15804:2014.
*** normalized to tensile strength in bending

TABLE 1. Reported values for global warming within past studies (sources given upon request).

façade elements made of SRC, CCC, and TRC with basalt or glass fibers by cradle-to-grave LCA. They identified no clear winner, though all TRC variants did better in 4 out of 6 LCIA indicators as compared to SRC. Hülsmeier et al. [6] showed in a cradle-to-grave LCA that CCC performed better than SRC on GW (-13 kg CO_2eq/m^2). A multifunctional, vacuum-insulated façade element made of CCC even outperformed that standard panel of CCC (-74 kg CO_2eq/m^2). Recently, Stoiber et al. [12] used EPD data to analyze bridge designs made of CCC, SRC, and steel. Again, CCC showed lower GW (-34 to -48%), but higher AP (-40 to 48%) scores. Those studies served as benchmark, but were partly limited in data availability, e.g. for carbon fiber fabric or end-of-life (EoL).

To address these research gaps, we compared variants of a prefabricated sandwich wall system and strengthening schemes for an existing concrete ceiling made of either CCC or SRC. Our research aims to identify hotspots for carbon concrete from an environmental perspective and is guided by following:

1. What environmental impacts are characterizing compared structural applications?
2. What level of energy and resource depletion is embodied in each material life cycle?
3. Is substitution of SRC with carbon concrete an eligible measure to foster circular economy?

We improved the analysis by collecting non-disclosed company data, updated materials for CCC, and integrated data from joint research projects, e.g. recycling processes. For practitioners, the results signal current hotspots along the value chain of carbon concrete to proactively start redesign strategies. Civil engineers will be enabled to discuss material choices within the early design process to improve environmental sustainability. For city planners, we illustrate indicators allowing to measure policy impact and scale. For scholars, we will add insights to existing research dialogues in the area of CCC and environmental sustainability. The method and data used in this article is described in Section 2. Results and discussion are presented in Section 3. Section 4 concludes upon our research objectives.

2. Materials and methods

We began with a scoping systematic review to maintain evidence-based research practices and identify comparable datasets. Table 1 illustrates a current

	Sandwich wall system		Ceiling slab reinforcement		
	Variant A1 (SRC, C25/30)	Variant B1 (CCC, prefab.)	Variant C (SRC, C25/30)	Variant D (CCC)	Unit
Inner / outer shell / height	0.19 / 0.08	0.14 / 0.03	0.047	0.006	m
XPS insulation	- 0.035 -		na		m
N.x (outer shell)	- 15 -		na		kN
Load capacity	na		- 5 -		kN/m^2
U-value	- 0.27 -		na		W/(m·K)
Sound insulation	77	71	na		dB
Concrete 25/30 (% in-situ)	601.7 (40%)	na	109.8 (100%)	na	kg/m^2
Special concrete for CCC	na	406.05	na	14.1	kg/m^2
Steel reinforcement B500	46.31	na	2.99 or 0	na	kg/m^2
Stainless steel B500 NG	1.04	na	0 or 2.99	na	kg/m^2
Carbon fiber fabric	na	2.16	na	0.65	kg/m^2
Polystyrene	- 2.7 -		na		kg/m^2
Net weight	651.75	410.91	112.99	14.75	kg/m^2

TABLE 2. Functional unit for two structural applications and life cycle inventory (own illustration).

lack of coherent knowledge: the range of reported values for just GW varies a lot. We see the importance of well-defined functional units: differences on level of basic materials, e.g. carbon fiber versus steel girders (up to +9, 118%), are substantially greater than on level of entire structures, e.g. CCC versus SRC used in façade panels (-15 to 73%).

2.1. FUNCTIONAL UNIT AND LIFE CYCLE INVENTORY

Our reference functional unit was defined as 1 m^2 of: a) a prefabricated sandwich wall made of SRC for a 3-storied building or b) a ceiling slab reinforcement of an existing SRC slab to increase load capacity from 1.5 to 5 kN/m^2. Each functional unit is not solely mass-based, but fulfils rated structural and mechanical requirements (see Table 2).

The wall systems were designed as non-stiffening sandwich outer walls with total dimensions 6 × 2.8 meters. We did not consider connections or cut-outs for existing openings, facades or corners. For the wall systems, we modelled four variants: two variants (A1-A2) of SRC with different concrete compressive strengths (C25/30 and C50/60) both using in part in-situ concrete. The two variants made of CCC (B1-B2) were dimensioned to meet the same requirements. Variant B1 was modelled as entirely prefabricated, the other B2 required partly in-situ concrete. The existing ceiling slab was 23.5 cm thick using C25/30. For the ceiling reinforcement, one SRC and CCC variant each (C and D) was calculated while assessing only the reinforcement materials.

Calculated material input data in Table 2 reveals: the special concrete for CCC amounts to 67.4%, respectively 12.8% of concrete C25/30 in variant A1 and C. Weight of steel reinforcement amounts to 460-2,192% of carbon fiber fabric. Total net weight differs by 240.84 (wall) or 98.05 kg/m^2 (ceiling).

2.2. SYSTEM BOUNDARIES AND CUT-OFFS

Our cradle-to-grave LCAs encompassed all life cycle stages except the use stage. We followed the nomenclature of EN 15804 for life cycle stages. Service life was assumed 50 years as suggested by German regulatory bodies. No extended service life scenario was applied.

Petroleum-based polyacrylonitrile (PAN) was used as precursor for CCC. For use stage, no conversion scenarios, replacement cycles or maintenance activities were expected. Component layers subject to wear, e.g. paint coats, were not considered, too. The base scenario for EoL: the wall is demolished, the building materials are separated and transported to dedicated plants for further processing. Based on findings of joint research center "C^3 Carbon Concrete Composite", we assumed that 95 percent of initial carbon fiber fabric was reclaimed for material reuse after processing by pyrolysis. Material reuse was modelled as producing glass fleece with recycled carbon fibers. Avoided production of primary glass fleece was credited. We also modelled "R8 Recycle" paths for concrete fraction, (stainless) steel, and insulation materials by road gravel, recycled steel, and thermal recovery.

For cut-offs, we neglected plants, machines, and infrastructure necessary for manufacturing and construction. The LCAs were mainly set-up for reference area Germany. For base scenario, transport distances for the materials ranged between 50 and 500 km. We used GaBi software version 9.2.0.58 SP 38 and CML-2015 as LCIA method. The dataset for carbon fiber rovings and a special fine-grained concrete mix "C3-B2-HF-2-145-5" similar to C80/95 was based on another research subproject [16] within joint research center "C^3 Carbon Concrete Composite". We used non-disclosed data of a manufacturer of carbon fiber fabrics and concrete plants otherwise generic datasets of GaBi.

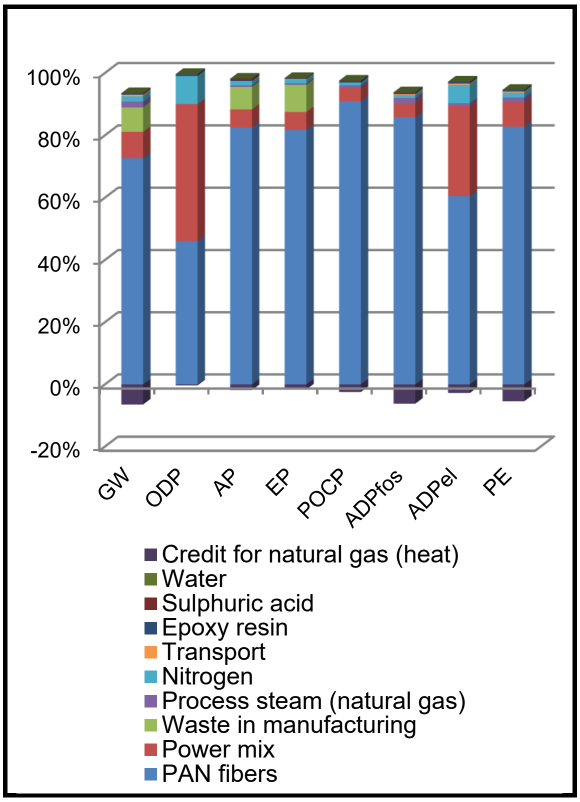

Figure 1. Hotspot analysis cradle-to-gate for carbon fiber fabric (own illustration).

3. Results and discussion

3.1. Hotspot analysis for single life cycle stages

First, we discuss hotspots identified within manufacturing and upstream activities (cradle-to-gate). Figure 1 shows results for the carbon fiber fabric. The manufacturing of precursor material and succeeding production processes (summarized as "PAN fibers") are the dominating influencing factors. Only ODP (ozone depletion) and partly ADP_{el} (abiotic depletion, non-fossil resources) are also strongly influenced by electricity consumed and its underlying power mix. Manufacturing companies, e.g. Toray, Hexcel, SGL Carbon or Teijin, should thus concentrate on corporate efficiency strategies within production and identify suitable green alternatives to natural gas. All other value chain members should increase the share of renewables within their power mix [11] to refer to circular economy strategy "R2 Reduce" [1]. Moreover, that industry cluster should foster research on alternatives to petroleum-based PAN like lignin (see Section 3.3) assorted to "R0 Refuse" [1]. For concrete, hotspot analyses are already published [17] and not displayed here.

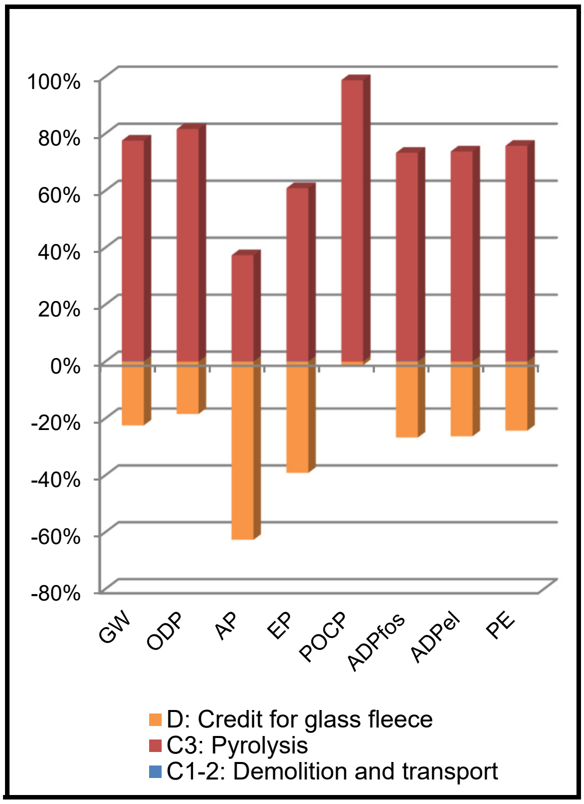

Figure 2. Hotspot analysis of the end-of-life stage for carbon concrete (own illustration).

Second, we look at the EoL stage in our base scenario. This includes demolition, transportation to pyrolysis plant, pyrolysis [18], manufacturing of a recycled carbon fiber fleece (a case of downcycling). Figure 2 shows a dissatisfying picture: pyrolysis is the dominating process due to its energy intensity. Except for indicator AP, none of the seven other environmental impact categories can be offset. The crediting along that "R8 Recycle" [1] pathway for the glass fleece production is not enough. Thus, current recycling technologies for carbon fiber fabric in CCC offers a true circular economy path, but has a negative net environmental effect, e.g. it requires more energy input than credited. Although better than facing difficulties like wind turbines [19], this is far from ideal.

3.2. Cradle-to-grave comparison

Results for the full life cycle illustrate a mixed picture. Exemplary, we show ADP_{fos} (abiotic depletion, fossil resources), PE, and GW scores for each considered life cycle stage (see Figure 3-5). For the wall system, each square meter of variant B1 made of CCC leads to lower carbon emissions (GW: -6.1 kg CO_2eq/m^2) but is characterized by higher energy intensity (PE: +238 MJ/m^2) and fossil resource depletion (ADP_{fos}: +263 MJ/m^2). Same is true for ceiling reinforcement: -2.6 kg CO_2eq/m^2, +94 and +74 MJ/m^2. Apparently, the value chain of carbon fiber and its fabric uses low-carbon power generation as compared to steel. Base scenario shows another

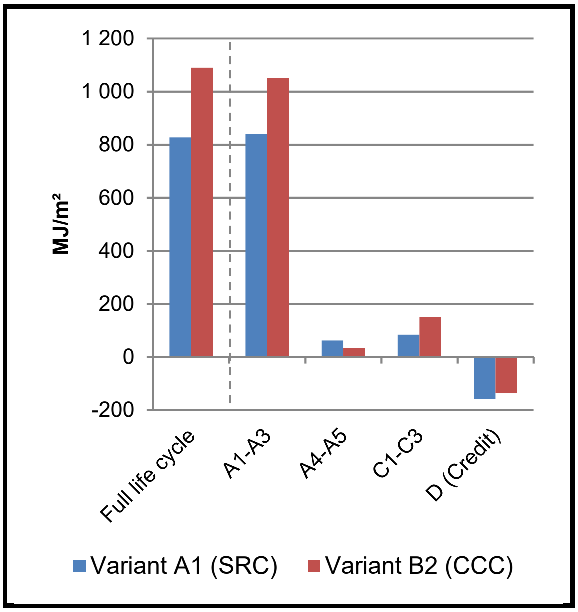

Figure 3. Comparing ADP_{fos} along all life cycle stages for wall systems (own illustration).

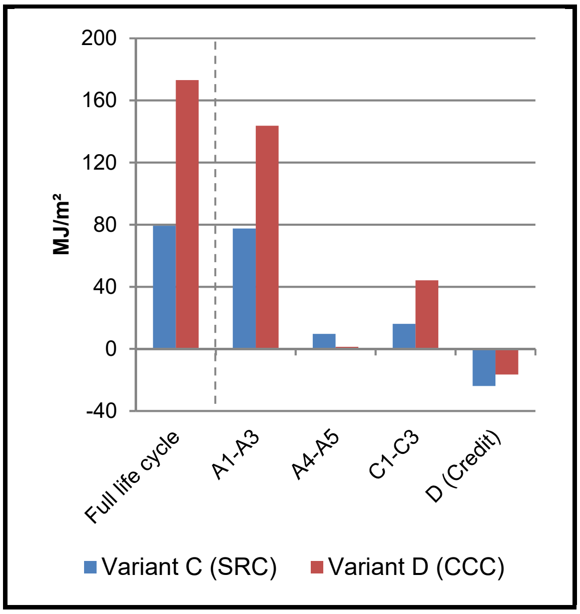

Figure 4. Comparing PE scores for ceiling slab reinforcements (own illustration).

comparative advantage for SRC with respect to recycling (PE: -108 MJ/m^2) and resulting credits (-36 MJ/m^2). About 85% of used steel derives from recycled and remelted material in German construction industry. This is an ongoing success story of a circular "R8 Recycling" [1] path already paying back for SRC. For indicators not shown here: CCC variant B1 keeps an advantage on AP and eutrophication (EP); ODP is roughly equal; SRC variant A1 has lower damage in photochemical ozone creation (POCP).

Figure 5 illustrates examined effects of four scenarios (violet bars): positive values imply an environmental advantage of variant B1 (CCC); negative values vice versa a disadvantage. For base scenario, variant B1 has lower GW scores (up to +11.9 kg CO_2eq/m^2) than all other design variants (blue bars). Scenario 1 assumed a 20% share of steel imported from China within the SRC value chain. This increased all LCIA indicators negatively for variant A1 (GW: +16.9). Scenario 2 modelled real location sites of carbon fiber and fabric manufacturers. The advantage of low-carbon water power generation in the US and Scotland is entirely offset by environmental impacts of the resulting long-distance oversea transportation (GW: -1.1). Scenario 3 ignored the EoL stage (GW: +14.8) and scenario 4 assumed a future reuse of recycled carbon fibers for the same purpose, namely carbon fiber fabric (GW: +16.4). This is a clear signal to foster that true recycling path. Sensitivity analyses tested for data uncertainty (orange bars): a dataset for steel reinforcement with -50% lower and a dataset for carbon fibers with +50% higher carbon emissions is chosen. The advantage for GW turns negative (GW: -7.8 / -6.8).

3.3. Limitations

As with any LCA, (model) choices were made with effects on overall results. First, we did not quantify the use of lignin-based PAN, though there is promising research that illustrates lignin as future, more sustainable sourcing. Other alternatives to high purity PAN, e.g. based on algae or waste cotton linter are rather at an experimental stage. Second, we did not study natural fiber materials, e.g. flax, jute, or sisal. They still lack a good balance of impact strength, stiffness, and toughness within the desired flexural and tensile properties. Both strategies would support "R0 Refuse" [1] and diminish the volume of petroleum-based PAN and geopolitical risks. Third, we did not explicitly model strategies towards green concrete. We used an optimized special fine-grained concrete mix that was developed and tested for CCC [16]. The benchmarking SRC was modelled with German average mix of C25/30 and C50/60 by the German Cement Works Association. Fourth, we did not account for recycled aggregate concrete or other types with recycled materials. As this is a feasible option for both, SRC and CCC, so we did not add this complexity to "R8 Recycling" [1]. Currently, crushed concrete was credited for road gravel. Fifth, future analyses could evaluate eco-designs related to modularity and removable joints. This path would follow circular economy strategy "R3 Reuse" [1]. Sixth, we do not include extended service life scenarios, yet.

4. Conclusions

Our study aimed to earmark comparative environmental advantages for the innovative building material carbon concrete and existing circular economy potentials. We applied cradle-to-grave LCA compar-

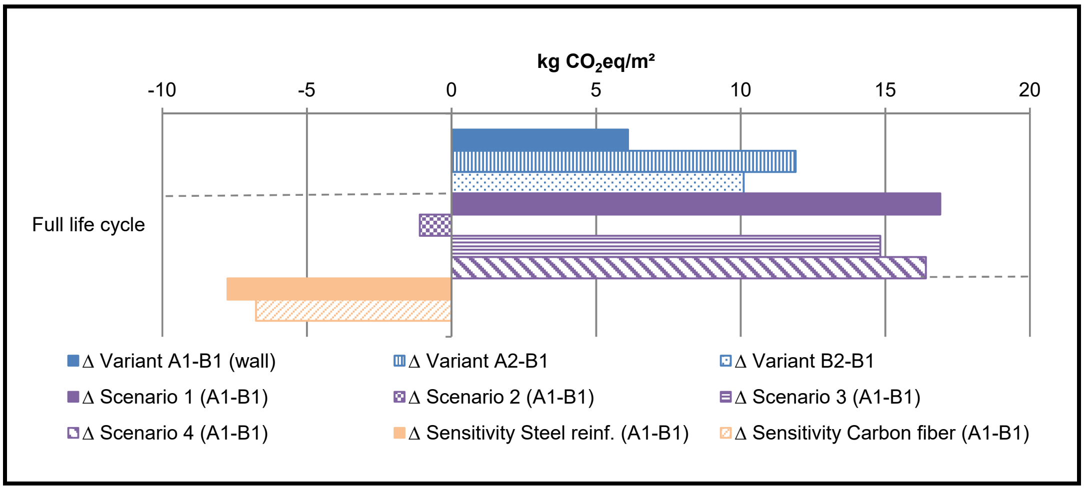

FIGURE 5. Difference in GW scores between wall system variants A (SRC) and B (CCC) for full life cycle of design variants, scenarios, and sensitivity analyses (own illustration).

ing SRC and CCC variants. Scope et al. [20] may meet expectations of the scholarly community framing LCA as main pillar of a life cycle sustainability assessment.

First, we identified hotspots of environmental impacts located in manufacturing stage of carbon fiber fabric and concrete as well as during recycling processes of CCC. Second, we quantified abiotic depletion and primary energy consumption for each material life cycle for a functional unit of 1 m^2. During manufacturing and construction stages, the examined wall system variant A1 made of SRC is less energy-intensive (ADP_{fos}: -181 MJ/m^2; PE: -102 MJ/m^2), but emits roughly +14% more greenhouse gases. For the full life cycle, both materials get closer on GW (+6%), but drift apart on ADP_{fos} and PE (-24%/-19%) in base scenario. Analogies are observed for the ceiling slab reinforcement: SRC keeps an advantage on ADP_{fos} and PE (-53/-54%), but emits +2.7 kg CO_2eq/m^2. Net weight of CCC structures is significantly reduced by 59% (wall system) and 665% (ceiling). Third, we have discussed a couple of realized or potential circular economy paths. Currently, trade-offs exists: using variant B1 for a whole 3-storied building could amount to increased primary energy of +107,957 MJ, but achieved savings of 109 tons materials and 2.8 tons greenhouse gases emissions. City planners then need additional sustainability criteria.

Overall, our assessment indicates that CCC provides a circular economy material loop, less material weight, and resulting lower carbon emissions. Carbon concrete may improve the climate mitigation potential of buildings, but industry and building professionals are encouraged to emphasize discussed technology pathways to improve energy intensity and specific circular economy strategies. We extensively discussed our study's limitations with room for further research in many fields. Practitioners shall not "overlook" [9] carbon concrete but study the new material and start piloting projects to empirically test estimated savings.

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