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BUILDING COMPONENTS AND BUILDINGS

Environmental assessment of a disruptive innovation: comparative cradle-to-gate life cycle assessments of carbon-reinforced concrete building component

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Abstract

Purpose How to build in more environmentally sustainable manner? This issue is increasingly coming to the fore in construction sector, which is responsible for a relevant share of resource depletion, solid waste, and greenhouse gas (GHG) emissions. Carbon-reinforced concrete (CRC), as a disruptive innovation of composite building material, requires less resources and enables new forms — but does it make CRC more environmentally sustainable than steel-reinforced concrete (SRC)? This article aims to assess and compare the environmental impact of 45 material and production scenarios of a CRC with a SRC double wall.

Methods The life cycle assessment method (LCA) is used to assess environmental impacts. The functional unit is a double wall and the reference flows are 1 m^3 for concrete and 1 kg for fiber. CML methodology is used for life cycle impact assessment (LCIA) in the software GaBi© ts 10.0. A sensitivity analysis focuses on electricity grid mixes, concrete mixes, and steel production scenarios.

Results The midpoint indicator climate change respective global warming potential (in kg CO_2e) ranges between 453 kg CO_2e and 754 kg CO_2e per CRC double wall. A comparable SRC double wall results in emissions of 611–1239 kg CO_2e. Even though less raw material is needed for CRC, it does not represent a clear advantage over SRC in terms of climate change. In a comparison, the production of steel (blast furnace vs. electric arc furnace vs. recycled steel) and the choice of cement type are of decisive relevance. For concrete mixes, a mixture of Portland cement and blast furnace slag (CEM III) is beneficial to pure Portland cement (CEM) I. For fiber production, styrene-butadiene rubber (SBR) has an advantage over epoxy resin (EP) impregnation and the use of renewable energy could reduce emissions of fiber production up to 60%.

Conclusion CRC requires less material (concrete cover) than SRC, however, exhibits comparable CO_2e to SRC — depending on the production process of steel. In the future, fiber production and impregnation should be studied in detail. Since in terms of climate change neither wall (CRC vs. SRC) clearly performs better, the two other pillars of sustainability (economic and social, resulting in LCSA) and innovative building components must be focused on.

Keywords Life cycle assessment · Carbon-reinforced concrete · Carbon fiber · Concrete · Steel · Building component · Construction

1 Introduction

The global building and construction sector, promoting economy (10% of global GDP) and social well-being by shelters and employment (100 million people) (Dong and Ng 2016), at the same time contributes significantly to resource depletion, energy consumption, and greenhouse gas (GHG) emissions (Janjua et al. 2019): 33% of global energy consumption, 40% of raw material consumption, and 40% of global solid waste generation are attributable to the construction sector (Akhanova et al. 2020; Choi 2019). CO_2

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emissions of the construction industry are responsible for about 39% of global emissions (Ding et al. 2016; Sameer and Bringezu 2018). Especially concrete, which is considered one of the least environmentally sustainable materials (~8% of CO_2 emissions), is required in high quantities for construction due to the need for reinforcing steel and new buildings (Martínez-Rocamora et al. 2016). Continuing with business as usual in the construction sector will lead to more than doubling of global raw material extraction until 2050 (Sameer and Bringezu 2018), thus to more resource depletion and more environmentally polluting emissions.

Since reinforced concrete is nowadays the most used and popular, but at the same time enormously resource-intensive building material in construction (Akhtar et al. 2015; Barros et al. 2017), innovations and resource- and emission-saving alternatives are needed: carbon-reinforced concrete (CRC) is considered a valid alternative to steel-reinforced concrete (SRC). CRC consists of a lattice structure of carbon fibers. Unlike steel, carbon fibers cannot rust, which is why no protection against corrosion is necessary and a small layer of concrete above and below the reinforcement is sufficient for the entire service-lifetime. In addition, the fibers allow new shapes that were not possible with steel reinforcement (Kortmann et al. 2018).

Life cycle assessment (LCA) has been recognized as a valid method to measure the environmental performance of materials and products. With the help of LCA, environmental performance of building materials, production steps, and services can be assessed and environmentally critical process steps can be identified (Ding et al. 2016; Dong and Ng 2016; Guinée et al. 2011; Guinée and Lindeijer 2002; ISO 14040 2006; ISO 14044 2018) at earliest possible stage of design and development of innovative materials.

The aim of this article is to identify CRC environmental performance and whether it is a promising alternative to SRC. In a detailed version, we provide a matrix compilation of different LCA scenarios of the innovative building material. As demonstrated in the state-of-the-art, to date, there are no full (more midpoint indicators than climate change respective global warming potential and cumulative energy demand (CED)), comprehensive, and detailed LCAs of CRC, as well as its application to building components. The environmental impact of CRC is determined taking into consideration today's production, possible optimization potential has been considered, and a comparison with SRC by considering the same functional unit has been assessed. Innovative aspects of this study are.

- The individual analyses of concrete and fiber with different impregnation,
- The consideration of different material and production variations (concrete and fiber),
- Life cycle assessments that go beyond the specification of cumulative energy demand and climate change,
- The consideration of different reference flows and the functional units as building components,
- A detailed and reproducible life cycle inventory (in Supplementary Material), and
- The direct comparison of CRC and SRC.

The results of this study serve research and practice in providing detailed insight in material composition, production, and optimization potential and in distinguishing in which form the innovation of CRC is preferable to already known materials from an environmental point of view.

2 State of the art

2.1 Environmental dimension of a life cycle sustainability assessment

With growing global awareness and importance of sustainability, there is increasing interest in the development of methods that contribute to a better understanding of the different impacts a building has in its life cycle. In this study, the focus is only on the environmental dimensions of a life cycle sustainability assessment (LCSA) (Finkbeiner et al. 2010; Kloepffer 2008): the LCA of reinforced concrete. LCA identifies, analyzes, and evaluates all impacts that a product, service, or building has on the environment during its life cycle (Ding et al. 2016; Finkbeiner (editor) 2015), starting from resource extraction up to the end of life (EoL). The assessment (LCA) is standardized according to ISO 14040 and ISO 14044 (ISO 14040 2006; ISO 14044 2018), and in the building sector additionally by ISO 15686–5 (ISO 15686–5 2017) and DIN EN 15,804 (Deutsches Institut für Normung (DIN) e.V. 2012). The structure of LCA, as stated in the standards (ISO norms), in general and in this article in particular comprises four phases, named as goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO 14040 2006; ISO 14044 2018). The LCA is considered the best methodology for evaluating the environmental impacts caused by a product during its life cycle in the construction sector.

2.2 LCAs in the building and construction sector

LCA studies in the construction sector have been available since 1997 (Adalberth 1997). Various reviews (Backes and Traverso 2021a; Benli Yildiz et al. 2020; Buyle et al. 2013; Martínez-Rocamora et al. 2016; Ortiz et al. 2009; Sharma et al. 2011) show that the results of diverse construction related LCAs are not easy to compare. System boundaries vary significantly and many studies do not consider the entire life cycle. The following aspects are excluded for example: transportation, waste factors, maintenance, water consumption, use phase, and end of life (Benli Yildiz et al. 2020; Buyle et al. 2013). The functional units vary from a whole building, over m^2, over number of lives in a house, over kWh/m^2/year, and over building components and material (Backes and Traverso 2021a; Buyle et al. 2013; Sharma et al. 2011). Furthermore, different lifetimes are assumed for the buildings or components, ranging from 1 year to 75 or even 100 years (Buyle et al. 2013; Sharma et al. 2011). The inclusion of regional factors such as location, climate, and technology as a result of studies conducted in different countries is often neglected (Benli Yildiz et al. 2020). The influence of different production sites (location, geographical differences) can have an impact on raw material sourcing, transport routes, technologies used and efficiency of these, energy used, and, by extension, on social and economic factors. Furthermore, there are also differences between the use and end-of-life phases, in the use phase in particular due to different climatic conditions, which influence early and late aging or, for example, corrosion; in the end-of-life, the state of the art in different countries and thus technologies and the use of energy compositions (purely renewable vs. nuclear power vs. coal power, for example) can have further influence. Accuracy also varies, i.e., some studies are crude and less detailed, considering only the most obvious products and processes (Buyle et al. 2013). Both midpoint and endpoint indicators are applied (e.g., CML, Eco-indicator99, and Carbon Footprint), sometimes a range of different methodologies are used, or results are examined to see if they meet policy objectives (Buyle et al. 2013). However, GaBi Database and Ecoinvent stand out for their integrity, ease of use, and dedicated resources, highlighted by Martínez-Rocamora et al. (2016). Less frequently, LCAs consider impact categories other than CED and climate change (Backes and Traverso 2021a). Many of these studies are simplified LCAs that only address the energy demand, especially the early studies. The results shed more light on building designs in general and less on the materials chosen (Backes and Traverso 2021a; Benli Yildiz et al. 2020; Buyle et al. 2013; Martínez-Rocamora et al. 2016; Ortiz et al. 2009; Sharma et al. 2011).

It is important to note at this point that we are not aiming for a literature review on LCAs in the construction sector, LCAs on steel-reinforced concrete, or LCA on carbon-reinforced concrete. The following studies are listed for the purpose of classification of the topic and are intended to illustrate the complexity of LCA in the construction sector.

Looking in more detail at the state of research of scientific LCAs on carbon-reinforced concrete, a literature search extended to basic materials such as carbon fiber–reinforced polymers (CFRP) and carbon fibers based on few studies on carbon concrete yields about 80 detailed and advanced studies. The studies consider a large variety of functional units, as for example 1 kg material (Maxineasa and Taranu 2018), 1 m unit length of a bridge system (Pang et al. 2015), 1 m^2 of sandwich wall (Scope et al. 2020), 1 m^2 of reinforced concrete (Williams Portal 2015), 1 m^3 of concrete (Zingg et al. 2016), or an experimental facade of 60 m^2 (Laiblová et al. 2019). Chen et al. (2020) addressed the environmental impact of strengthening methods made of a carbon fiber-plastic composite, while Zhou (2013) conducted a comparative LCA of two alternative structural reinforcement techniques, both adopted a cradle-to-gate LCA approach (Chen et al. 2020; Zhou 2013). A cradle-to-grave approach was presented by Das (2011) (FU = 1 kg). Williams Portal et al. (2015) investigated textile-reinforced concrete (TRC) as a building material in a cradle-to-gate LCA (FU = 1 m^2), with carbon fiber and steel reinforcement also being part of the study (Williams Portal et al. 2015). Laiblová et al. (2019) compared carbon fiber–reinforced TRC facades with ordinary steel-reinforced concrete (Laiblová et al. 2019). Maxineasa and Taranu (2018) investigate pultrusion molded carbon fiber strips used to reinforce concrete structures (Maxineasa and Taranu 2018). Ibrahim et al. (2020) compare a carbon fiber reinforcing bar to a steel reinforcing bar in a cradle-to-gate LCA (Ibrahim et al. 2020). Scope et al. (2020) designed a LCSA to compare exemplary building components and retrofit scenarios based on CRC with those made of SRC (Scope et al. 2020).

For SRC, a large number of studies have been published. The objects studied vary widely and include, for example, reinforced concrete structures in detail (Li et al. 2019), concretes (Abdulkareem et al. 2019; Ding et al. 2016; Knoeri et al. 2013; Xia et al. 2020), ceiling designs (Brambilla et al. 2019; Hájek et al. 2011), and strengthening techniques (Palacios-Munoz et al. 2018). The different studies have been carried out all over the world (e.g., Ding et al. 2016; Dong and Ng 2016; Evangelista et al. 2018; Maia de Souza et al. 2016) and consequently considered different construction methods, transport routes, and/or types of manufacturing. Different units were used as the FU for which the environmental impact was determined: as 1 m^3 concrete (e.g., Ding et al. 2016), a building construction project (Dong and Ng 2016), m^2 area of the building per year (e.g., Evangelista et al. 2018), kg of reinforcing material or m of reinforcing span (e.g., Palacios-Munoz et al. 2018), concrete structure with specific structural form and mechanical properties (e.g., Xia et al. 2020), and the construction and maintenance of 1 m^2 of exterior wall (Maia de Souza et al. 2016). The main focus in all studies was on climate change (in kg CO_2e).

Since the aim of this study is not a literature review, we present some examples of studies mentioned above in more detail in order to be able to rank the results of this study — with its focus on CRC in comparison to SRC

— in terms of completeness, consistency, and plausibility. In Table 1, climate change (CC) in kg CO_2e values were extracted from previously published studies, focusing CRC and SRC. The studies presented below have conducted an extensive and comprehensible LCA, the data basis is presented and explained, all results are reported in absolute numbers, and correspond to a comparable functional unit (or reference flows) and system boundaries. Unnamed studies, without claiming to be complete, have deviations or missing information with regard to data, functional unit, system boundaries, or results presented (e.g., in percentage). Table 1 differentiates in coating, carbon fiber, steel, concrete, and reinforced concrete, resulting in a range of kg CO_2e values for the reference flows or FUs of mass (1 kg, 1 t) or volume (1 m^3) (Table 2), assessed for the system boundaries of cradle-to-gate. In addition, we integrated also a reference value for concrete from the Environmental Product Declaration (EPD) (A1–A3 = cradle-to-gate) (ibu-epd 2021).

None of the named studies considered and compared a functional unit at building component level (double wall), none made the direct comparison to steel-reinforced concrete, and additionally and especially, none used different concrete and fiber compositions, so that opportunities and risks can already be identified in the individual components, and the individual and reproducible inventory data. Furthermore, the current study represents a much greater level of detail, as the complete inventory as well as the process selection is presented in detail in the Supplementary Material.

Short digression: the double wall — our functional unit: The double wall in general offers an alternative to conventionally formed concrete walls, as it is an industrially prefabricated wall system. The double-skin wall element can be used as a statically loadable wall panel both in multi-storey construction and in basements and underground garages. This semi-prefabricated wall (double wall) consists of two wall shells, which are connected with lattice girders. The wall elements contain the statically required main and transverse reinforcement at the factory. Casted with in situ concrete, the overall cross-section looks like a monolithically manufactured wall. The result and the advantage of the double wall are perfect surfaces and a fast, economical construction process, as formwork is no longer required on site. In the example presented here, the basis for comparison of carbon- and steel-reinforced concrete are functionally identical components made of carbon and reinforced concrete in precast construction, which are equivalent in their load-bearing

Table 1 Example of published studies and results in climate change with cradle-to-gate system boundaries

Related to	Reference	Study focus	FU	CC in kg CO_2e
Coating	(Stoiber et al. 2021)	Epoxy resin	1 kg	5.8
Coating	(Stoiber et al. 2021)	Epoxy resin	1 kg	8.6
Carbon fiber	(Stoiber et al. 2021)	Carbon fiber	1 kg	11.4
Carbon fiber	(Stoiber et al. 2021)	CFRP (textile)	1 kg	18.4
Carbon fiber	(Stoiber et al. 2021)	CFRP (rebar)	1 kg	19.7
Carbon fiber	(Das 2011)	Carbon fiber	1 kg	24.2
Carbon fiber	(Hohmann 2019)	Carbon fiber	1 kg	26.4
Carbon fiber	(Das 2011)	Carbon fiber (PAN)	1 kg	31
Steel	(Gomes et al. 2013)	Steel (EAF)	1 kg	0.61
Steel	(Suer et al. 2022)	Steel (H_2 + direct reduction)	1 kg	0.78
Steel	(Backes et al. 2021)	Steel	1 kg	2.1
Steel	(Suer et al. 2021)	Steel	1 kg	2.1
Steel	(Chisalita et al. 2019)	Steel	1 t	2.1
Steel	(Stoiber et al. 2021)	Steel (reinforcement)	1 kg	2.3
Steel	(Stoiber et al. 2021)	Steel (hot-dip galvanized)	1 kg	2.8
Steel	(Buchart-Korol 2013)	Steel	1 t	2.5
Concrete	(Stoiber et al. 2021)	Concrete (C30/37)	1 m^3	232
Concrete	(Knoeri et al. 2013)	Concrete (C42.5)	1 m^3	280
Concrete	(ibu-epd 2018)	Concrete (C50/60)	1 m^3	300
Concrete	(Stoiber et al. 2021)	Concrete (C50/60)	1 m^3	335
Concrete	(Abdulkareem et al. 2019)	Conventional concrete	1 m^3	350
Concrete	(Xia et al. 2020)	Concrete structures	1 m^3	359–618
Concrete	(Ding et al. 2016)	Natural and recycled aggregate concrete	1 m^3	403
Concrete	(Stoiber et al. 2021)	Concrete (C70/85)	1 m^3	431
Reinforced concrete	(Abdulkareem et al. 2019)	Steel fiber–reinforced concrete (19.32 kg/m^3)	1 m^3	450

Table 2 Steel- vs. carbon-reinforced concrete

		SRC	CRC
Concrete cover	Corrosion	Yes	No
	Minimum concrete cover	20–55 mm (Otto and Adam 2019)	5–10 mm (Kortmann 2020)
	Service life [years]	50 (Kortmann 2020)	> 50 (Kortmann 2020)
Performance	Tensile strength [N/mm^2]	550 (Otto and Adam 2019)	3000 (Otto and Adam 2019)
	Weight-specific performance [kN/g] for same dimensions	7 (Otto and Adam 2019)	167 (Otto and Adam 2019)
Concrete composition	Type	High strength (often (Kortmann 2020))	Normal strength (often (Kortmann 2020))
Reinforcement	Type	Bar and mat shape — closely meshed (Kortmann 2020; Stahr 2015)	bar and mat shape (Kortmann 2020; Stahr 2015)

capacity. The same functionality results in components with different dimensions (Otto and Adam 2019).

3 Building materials considered in the study

3.1 Carbon-reinforced concrete

Carbon-reinforced concrete is a composite construction material made of concrete and carbon fibers. Concrete forms the basis for both composite materials (CRC and SRC). Concrete consists of a mix of cement, aggregates, concrete additives (admixtures), and water (Stahr 2015). The composition of these starting materials and the respective material properties influence the workability of fresh concrete and subsequent properties of the hardened concrete. Therefore, the composition of concrete must be specifically planned so that it can meet requirements from the environment and use, such as frost resistance and durability (Stahr 2015). Cement, as part of concrete, consists primarily of limestone and clay, and in most cases also of quartz sand and iron ore (Wietek 2019). After grinding and burning processes at 1400 to 1500 °C, the so-called cement clinker is produced. This is mixed with further additives such as granulated blast furnace slag, fly ash, or limestone and ground (Grimm 2014) — resulting in cement, a hydraulic binder which, with the addition of water, forms a cement paste and solidifies (Stahr 2015). Concrete is processed as fresh concrete and acquires its dimensionally stable property only after the chemical reaction between cement, water, and the subsequent hardening processes. Twenty-four hours after the addition of water, concrete has largely solidified; nevertheless, the solidification process is only complete after 4 weeks to several months (Grimm 2014).

Carbon fibers are used, among other products, to produce the reinforcement of CRC. They consist of carbon-containing materials and are produced artificially. Due to their low density and good mechanical properties as well as processability, they are appreciated reinforcing fibers in fiber composite construction (Kortmann 2020). The starting material for carbon fibers produced for the construction sector is mainly polyacrylonitrile (PAN), made of petroleum. PAN-based fibers are produced from the starting material PAN using solvents. These are drawn and pre-stretched in a wet-spinning process, which straightens the molecular structure for the desired fiber properties. This is followed by further post-treatment, which consists of washing, drying, and sizing. Finally, the PAN-based fibers are wound onto spools (AVK 2014; Kortmann 2020). The conversion process of PAN-based fibers to carbon fibers includes stabilization and oxidation (1), carbonization (2) and possible graphitization (3), and surface treatment (4) of the fiber (Kortmann 2020), being energy intensive process steps. Values compiled from the literature vary between an electricity demand of 32.4 to 200 MJ/kg and a thermal energy requirement of 97.69 to 200 MJ/kg for the production of carbon fibers (Hohmann 2019). This is followed by the impregnation application, which allows the surface properties of the fiber to be specifically adjusted. The fiber is pulled through a sizing bath and absorbs a predetermined amount of impregnation and water. In the construction industry, a distinction is usually made between two impregnations, depending on the desired stability and flexibility of reinforcing scrim: epoxy resin (duromers; EP) or styrene-butadiene rubber (elastomers; SBR) (Kortmann 2020).

CRC refers to a new type of composite material. The material is categorized as a textile concrete because, unlike conventional fiber concretes, the fibers are not added loosely to the fresh concrete mix but are present as so-called continuous fibers in a fixed lattice or bar form (scrim). As a result, the reinforcement can be arranged in the tensile zone of a component in line with the force flow. Carbon-reinforced concrete thus combines an already known advantage of reinforced concrete with a high load-bearing capacity of carbon fibers. To produce the reinforcement, up to fifty thousand filaments (individual fibers) are bundled into long fibers and following into a roving. In textile machines, the rovings are processed into carbon fiber rods or a flat, grid-like scrim. Depending on the application of the carbon scrim, flexible matrices (for curved components, for example) or stiff matrices (for the production of large-format reinforcing scrims) are used (Kortmann 2020).

3.2 Steel-reinforced concrete

SRC is a composite material consisting of concrete and a reinforcement of steel (Weber 2013). Among all, steel-reinforced concrete is the most widely used building material in the construction sector (Stoiber et al. 2021). The steel industry in Germany can be considered as one of the countries' most important sector. With an annual production of 42 million tons, it is even one of the largest crude steel producers worldwide. About 35% of the produced steel is used for the construction industry (14.7 million tons). In addition, about one-eighth of this amount is further used for reinforcing steel in concrete (1.8 million tons) (Seifert and Lieboldt 2020). Taking a look at the production of steel, two different processes are mainly used (Helmus and Randel 2014): basic oxygen steelmaking (BOS) and electric arc furnace (EAF). The production process of BOS, also known as the primary route, currently accounts for over 60% of the total crude steel production. Even though this production method is seen as efficient, it is highly carbon-intensive. Consequently, EAF has gained in importance in recent years owing to ecological benefits of this process (Helmus and Randel 2014). To be in line with EU targets (carbon neutrality by 2050), further carbon mitigation techniques have been developed (or are currently in development) for the steelmaking industry (Backes et al. 2021). An example is the hydrogen-based direct reduction processes as promising carbon–neutral steelmaking (Suer et al. 2022).

The popularity of SRC can be explained due to its beneficial characteristics (Stahr 2015). SRC is characterized by its economic efficiency, durability, and ready availability of raw materials (Poursaee 2016). Looking at the steel supplier network, it is characterized by short transport routes carried out by medium-sized concrete steel suppliers (Kortmann 2020). The advantages, however, are countered by disadvantageous properties. To provide general resistance and protection against corrosion, a minimum concrete cover must be maintained (Stahr 2015). A minimum concrete cover can be described as a barrier of concrete which suits as a physical and chemical corrosion resistance (Poursaee 2016). In general, a larger diameter of installed steel requires a thicker concrete cover (Stahr 2015).

3.3 Mechanical and material differences of CRC and SRC

When using CRC, concrete savings of about 50% can be achieved with the same static properties (Adam 2018) (Table 2: concrete cover), due to the corrosion resistance. The minimum concrete cover of 5–10 mm must be observed for all exposure classes when using a stainless reinforcement to ensure durability (Kortmann 2020). Consequently, no minimum concrete cover is required to protect the reinforcement from corrosion. Table 2 shows main differences between CRC and SRC.

Due to the low density of carbon, its performance in terms of weight is even greater in comparison, being almost 24 times greater than that of reinforcing steel (Otto and Adam 2019) (Table 2: performance). Since different concretes are used depending on the project and the CRC innovation, it is difficult to compare or differentiate the concrete used for steel and carbon, as for both similar concrete can be used. Differences and the rationale for diverse concrete mixes are primarily due to different strength classes of concrete and possibly different ways of manufacturing the component. As example, the extrusion process allows a much simpler integration of the reinforcement compared to 3D concrete printing. High demands are placed on the rheological properties of fresh concrete for the extrusion process, as the concrete must be transportable in the extruder. Another difference between CRC and SRC lies in the delivery network of the reinforcements. While steel reinforcement is characterized by fast procurement and short delivery routes, carbon components have to be supplied over much longer distances (Kortmann 2020). Despite the differences mentioned above, both reinforced concretes (CRC and SRC) can be used in equivalent performance — which is shown in this LCA with the example of a reinforced double wall.

4 Methodology

4.1 Goal and scope

The aim of the LCA scenarios in this paper is to present the environmental impact range of cradle-to-gate scenarios of CRC — determined in the design stage, hotspots, and optimization approaches will be identified, a comparison with SRC is made.

The following scenarios are based on ISO 14040/44 (ISO 14040 2006; ISO 14044 2018). The impact categories used are those in CML2001 (August 2016) (CML - Department of Industrial Ecology 2016): abiotic depletion (ADP elements [kg Sb eq.], ADP fossil [MJ]), acidification potential (AP [kg SO_2 eq.]), eutrophication potential (EP [kg Phosphate eq.]), freshwater aquatic ecotoxicity (FAETP inf. [kg DCB eq.]), global warming potential (GWP [kg CO_2 eq.]), human toxicity potential (HTP inf. [kg DCB eq.]), marine aquatic toxicity (MAETP inf. [kg DCB eq.]), ozone depletion potential (ODP, steady state [kg R11 eq.]), photochemical ozone

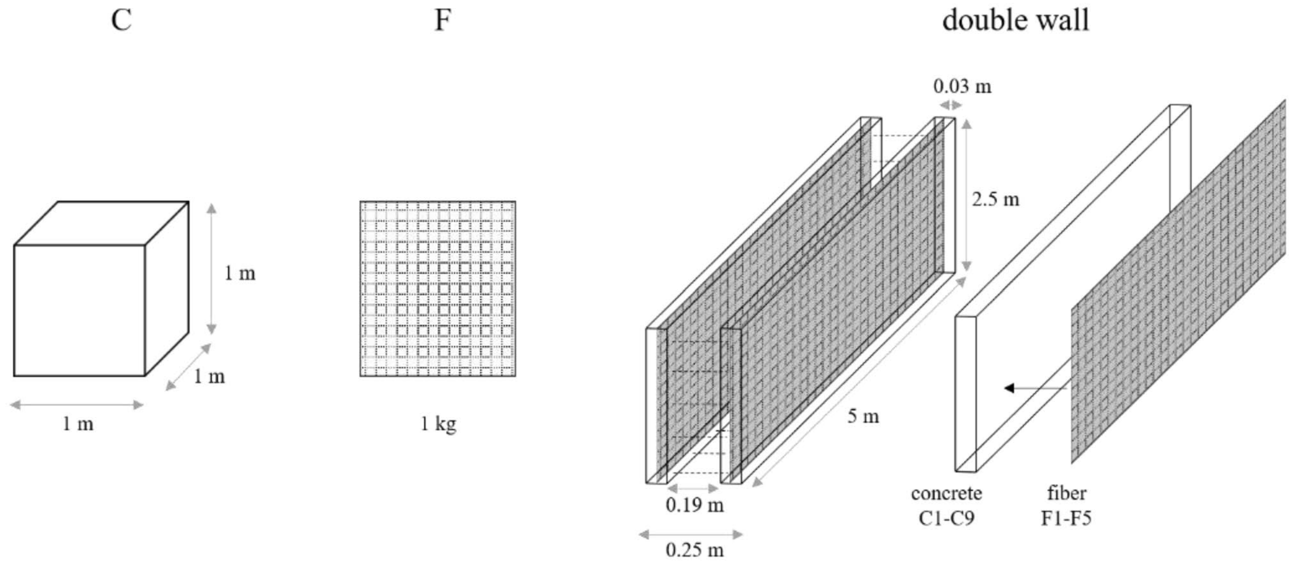

Fig. 1 Reference flows and functional unit

Table 3 Volume and reinforcement for double wall (Otto and Adam 2019)

Carbon-reinforced concrete	Amount	Unit	Steel-reinforced concrete	Amount	Unit
Total weight	1.43	t	Total weight	2.86	t
Total double wall	0.6	m^3	Total double wall	1.1	m^3
Concrete per double wall	1.42	t	Concrete per double wall	2.63	t
Carbon scrim per m^3	0.0170	t	Steel scrim per m^3	0.2100	t
Carbon scrim per double wall	0.0102	t	Steel scrim per double wall	0.2310	t
Carbon scrim per wall	0.0051	t	Steel scrim per wall	0.1155	t

creation potential (POCP [kg Ethene eq.]), and terrestric ecotoxicity potential (TETP inf. [kg DCB eq.]).

For comparison reasons, the FU and reference flows for the current study were differentiated in.

The functional unit of a double wall for the composite material (5 m × 2.5 m × 0.03 m) (Fig. 1) (according to Otto and Adam 2019),

The reference flow of 1 m^3 for concrete (C) only (in accordance with product category rules), and.

The reference flow of 1 kg for fibers (F) only (in accordance with product category rules).

The reason for the FU and different reference flows were:

Simplified comparison possibilities to previous studies (in m^3, kg, or t) (Table 2) and thus a plausibility check of the current results,

Construction component comparison to steel-reinforced concrete and its function, and.

In the possibility to show the challenge of the functional unit selection in LCA.

The baseline scenario represents a combination of Portland cement and PAN-based fiber with EP impregnation, produced in Germany (C1/F1). In total, nine concrete mixes (C = concrete (C1–C9)) and five carbon-scrim reinforcements (F = fiber (F1–F5)) (Fig. 1, Table 3) are represented, as well as 45 (9 × 5) different scenarios, supplemented by varying electricity mix, concrete mix, and steel processing ("2.18"). The reason for the different scenarios is that there is not a single concrete mix or a single fiber and impregnation combination for a carbon concrete component. Through the scenarios, we try to represent a whole range of possible realities and at the same time also show what material compositions with the lowest and highest possible emissions are. The detailed changes in concrete mixes and fiber compositions are shown in more detail below.

Mass differences between a carbon-reinforced double wall and a steel-reinforced double wall are shown in the following Table 3 — concrete in tons (t) needed for a carbon reinforcement is defined as 1.42 t compared to 2.63 t of concrete needed for a steel reinforcement (Table 3).

The double walls, whereof each wall is reinforced by a carbon fiber or steel matrix (Fig. 1), are additionally connected to each other in reality by a composite grid. This is shown in Fig. 1 as a black dotted line between the two walls. Such a composite grid can, for example, be made of

AR glass textile (von der Heid et al. 2019) or of steel. This composite lattice (connecting pins) was not named in Otto and Adam (2019), which is why it is not included in the current model. Moreover, possible insulation was also not considered in this LCA.

The system boundaries are designated as cradle-to-gate (= EPD A1-A3 in DIN EN 15,804 (Deutsches Institut für Normung (DIN) e.V. 2012)). The use and EoL phases are not part of this study: The use phase differs depending on the function, which is why it is difficult to clearly assess it. The EoL phase is briefly outlined below, but requires research and assessment work due to the innovation of CRC. The equipment and machinery themselves used for production are not included within the study. The energy, however, required for these machines — such as the concrete mixer or the scrim production machine — is included in the balance sheet, based on primary and literature data (see Supp. Material). The scenarios assume production in Germany and Japan. Further scenarios consider the use of renewable electricity mixes, based on current German data from 2020 (Umweltbundesamt 2021). In the fiber production, about 5% cutoffs (by, e.g., cutting fibers) are assumed (by ita, RWTH Aachen University, Hohmann (2019)), which are fed to landfill and then converted in and fed into the grid as energy (through combustion; credit given). The transports between raw material (-extraction) and further processing are assumed with a general average distance of 100 km each and are transported by truck, operated with diesel. For a scenario with oversea production (Japan), a ship transport is assumed (see Life Cycle Inventory in Supp. Material).

4.2 Life cycle inventory and data availability

Conservative approaches were used in the selection of processes and also in the assumption of data, when not given as primary or clearly defined literature data. Country-specific datasets were used as far as possible; where this was not feasible, first European and then global datasets were used. All data generated or analyzed during this study are included in this published article and its supplementary material (Supp. Material) — showing various concrete mixes and fibers including impregnation.

4.2.1 Concrete

Concrete (C1–C9) was modeled and evaluated in 1 m^3. C1–C5 represent concretes with primary data from RWTH Aachen University and TU Dresden University used in a specific project consortium (SFB TRR 280 2022), which can be used in particular for innovative processes of carbon concrete production: The concrete mixes C1–C4 are compositions based on primary data from RWTH Aachen University (Kalthoff et al. 2021). These mixes (C1–C4) were designed in particular to implement innovative manufacturing processes such as extrusion or 3D-printing of reinforced concrete. Components are Portland cement, quartz sand, sand, fly ash, silica sand, methyl cellulose, water, and PVA fiber. The masses in kg/m^3 vary, as can be seen in the Supp. Material (Tab. A1–A4). All mass data are primary data (Kalthoff et al. 2021). C5 is a concrete mix resulting from TU Dresden, Germany (Neef et al. 2020). This mix has been developed for innovative approaches as 3D-print (Table 4). C6–C9 (variation in raw material composition) are concrete mixes taken from published literature (secondary data) or defined as project reference concretes (C8 and C9) for the current project (SFB/TRR280, E01) (primary data) and used for the known and reinforced casting methods (for detailed concrete mix, please see Supp. Material): Especially for the raw materials cement and sand, GaBi© databases offer a variety of cement strength classes (e.g., CEM I 52.5 vs. 42.4 vs. 32.5), grain sizes (e.g., grain size 0/2 vs. 0/4), and allocation of emissions (e.g., allocated binders vs. burden free binders). Before choosing processes, we evaluated the individual processes and their respective impacts. There is little difference in the balances of strength classes and allocation (< 5% in kg CO_2e/m^3). For sand, grain size resulted in more differences, as did dried or undried sand. In general, the most conservative option (highest CC/global warming (GWP) results) was chosen when selecting the processes, unless a very clear process had to be selected according to input streams. Concrete transports were assumed with an average German-wide distance of 100 km (GLO: truck, Euro 4, 28–32 t gross weight/22 t payload capacity) for each mix ingredient. The energy data for C1–C4 are primary data (measure throughout a cooperation with ibac, RWTH Aachen University). Since the place of manufacture is Germany, mainly database and processes data refer to a manufacturing process in Germany (Supp. Material: Table A1–A4). One exemplary inventory is shown for C5 (Table 4). The other mixes are reported in Supp. Material to improve the readability of the paper.

The inventory tables show different concrete compositions with the corresponding GaBi© or Ecoinvent processes necessary for modeling 1 m^3 (reference flow) concrete. Further expansion was possible with the extension databases in GaBi©: II Energy, XIV Construction materials, XV Textile finishing, XXII Carbon composites, or in the Ecoinvent 3.6 (2020.2) database. Corresponding assumption and reason were given in the respective tables (see Supp. Material).

4.2.2 Carbon fiber and impregnation

The reference flow for consideration and evaluation of fibers was defined as 1 kg (Fig. 1). In order to create a wide range and possibilities for comparison, different datasets on carbon fibers were selected. It reflects carbon fibers which are

Table 4 Example concrete life cycle inventory (Neef et al. 2020), C5

Material	Amount				
	Unit	Input	GaBi© process	Assumption/reason	Data source
CEM I 52.5 R ft	kg/m^3	392.4	DE: cement (CEM I 52.5) Portland cement (burden free)		1 (primary)
Fly ash		214	DE: fly ash		1
Microsilica suspension		214	DE: silica sand (flour)	No further specification possible	1
Sand 0.06–0.02		252.8	DE: sand (grain size 0/2)	Grain size is not the correct one, could not be specified due to databases	1
Sand 0/1		252.8	DE: sand (grain size 0/2)	Grain size is not the correct one, could not be specified due to databases	1
Sand 0/2		758.5	DE: sand (grain size 0/2)		1
Superplasticizer		10.7	DE: concrete admixtures — plasticizer and superplasticizer — Deutsche Bauchemie e.V. (DBC)	Single suitable process	1
Water		138.7	DE: tap water from surface water		1
Transport					
Truck	km	100	GLO: truck, Euro 4, 28–32 t gross weight/22 t payload capacity	Assumed distance from raw material to next process step. Driven by diesel (GaBi© EU process) — amount of fuel (diesel) depending of weight	2 (secondary)
Energy					
Concrete mixing	kWh/m^3	9.2	DE: electricity grid mix	(Dorer and Hahn 2015; Sjunnesson 2005)	2

already embedded in a plastic matrix as well as carbon fibers for which this step had yet to be modeled. Impregnation was partly chosen to make the raw carbon fibers comparable to carbon fiber–reinforced plastics, impregnated with EP or SBR. The selection of carbon fiber processes was based on the named databases and the respective process descriptions. F1–F5 represent carbon fibers, which differ in the country of production (Germany and Japan), energy demand, and coating (EP vs. SBR) (secondary data).

For F1 (baseline scenario), the fibers concerning the respective process description are impregnated with EP in a bath by pultrusion — given by the used Fraunhofer dataset (GaBi© dataset). F2 varies from F1 only in the energy defined by Fraunhofer for the production of the carbon fiber–reinforced plastic parts. F3 initially represents an uncoated fiber (Gabi© database, Fraunhofer dataset), which is individually interwoven and impregnated. In this process, a 5% blend is assumed (according to the Institute of Textile Technology, RWTH Aachen University, and Hohmann (2019)), resulting in landfill and fed back as energy into the grid. According to a data sheet from V.Fraas Solutions in Textile GmbH (2017), the weight for a 1 m^2 impregnated carbon grid is 417 g. For a 1 m^2 carbon grid, the weight is 309 g if uncoated (V.Fraas Solutions in Textile GmbH 2017). Therefore, a difference of 108 g can be calculated, which is due to the impregnation. Since SBR and EP have approximately the same density, this difference plays a negligible role and 108 g were assumed as impregnation — upscaled to 1 kg or a double wall. Raw fibers are impregnated with coatings, for which the corresponding energy was assumed by Hohmann (2019): The named processes resin preparation/mixing, resin coating, resin impregnation, winding, and air conditioning were summed up and assumed as feasible for our needs. This resulted in 3.8 MJ/kg (= 1.05 kWh/kg) (Supp. Material: Tab. A11). In F3, complete production and impregnation in Germany was assumed. F4 represents the same production as F3, located in Japan (JP) (Table 5) — further inventory details can be found in the Supp. Material.

F5 is also similar to F3, but these fibers were impregnated with SBR (Supp. Material).

Due to the lack of detailed German primary data on fibers, only GaBi© datasets were considered. The dataset and the selected process for the coated fibers in F1 were chosen from the GaBi© database XXII carbon composites, which was developed by Fraunhofer IGVC, Germany (Fraunhofer IGVC 2021). The assumption for transport is the same to that made for the concrete mixes. Long-distance transports are carried out by cargo ship since most transports are handled by sea (Stölzle and Lampe 2012) (GLO: container ship, 5.000 to 200.000 dwt pay load capacity, ocean going), no aviation cargo was assumed.

4.2.3 Scenarios

To evaluate the sustainability performance of CRC and to determine a worst-case and a best-case scenario, as well as

Table 5 Example fiber life cycle inventory, F4

Material	Amount				
	Unit	Input	GaBi© process	Assumption/reason	Data source
Raw fiber	kg/m^2	0.32	JP: carbon fiber–reinforced plastic part — 14	0.3245 kg/m^3 input assumed, as 5% are expected to be blend. Resulting in 0.309 final fiber	2
Epoxy resin	kg/m^2	0.11	DE: epoxy resin (EP) mix	Difference concerning V.Fraas solutions in textile GmbH (2017) of impregnated vs. un-impregnated fibers	2
Credit blend raw fiber	kg/m^2	0.02	EU-28: textile landfill	5% blend = 0.01545 kg/m^3 — based on 0.309 kg/m^3 (fictive facade panel); only one process available. Resulting in energy fed into the grid (JP)	2
Transport					
Ship from JP to DE	km	20,000	GLO: container ship, 5.000 to 200.000 dwt pay load capacity, ocean going	Biggest ship assumed — amount of fuel (heavy fuel) depending on weight	2
Truck	km	100	GLO: truck, Euro 4, 28–32 t gross weight/22 t payload capacity	Assumed distance from raw material to next process step. Driven by diesel (GaBi© EU process) — amount on fuel (diesel) depending of weight	2
Energy					
Production of carbon scrim	kWh	1.05	JP: electricity grid mix	(Hohmann 2019)	2
Impregnation	kWh	0.44	DE: electricity grid mix	(Hohmann 2019)	2

to define hotspots and optimization approaches, a combination of the presented individual concrete compositions and fiber compositions followed in the scenarios. A matrix of 45 composite possibilities was created. The scenario concrete mixture C1 and fiber F1 (C1 and F1) represents our baseline scenario — from where all further scenarios vary (for example with regard to the concrete composition, in the fiber impregnation or the production load of the fibers). For this, the semi-finished carbon product and the necessary concrete mix must be transported to the manufacturing site and combined. For this, the transports of fiber matrix and concrete to another plant were assumed with an average of each 100 km (GLO: truck, Euro 4, 28–32 t gross weight/22 t payload capacity). The required combination energy could not be found in literature and there was no information provided by primary data. It is certain, however, that the concrete must be compacted (Kampen 2013), which is why the assumption was made that a formwork vibrator would be used in this case. This is common practice for precast concrete elements. Furthermore, an application time of the vibrator of 5 min was assumed for the area of a 1 m^2 fictive scrim, respective 0.02 m^3 concrete (10 mm each side). A suitable device for this purpose is, for example, the AR26 external vibrator from Wacker Neusen. This has a motor power of 0.3 kW and thus results in an energy consumption of 0.025 kWh for an application duration of 5 min (Neuson 2021), respective 1 m^2 or 0.02 m^3. Following, per 1 m^3, 1.25 kWh and per 0.6 m^3 (CRC), 0.75 kWh, or 2.7 MJ were assumed (Eq. 1).

$$\frac{0.025kWh}{0.02m^3} = 1.25(\frac{kWh}{m^3}) \quad (1)$$

Final products "leaving" these models are the manufactured (CRC) double walls as well as resulting impacts and waste streams.

4.3 Life cycle impact assessment

For a better understanding of the following life cycle impact assessment, the summary of the abbreviations is shown as a legend (Table 6).

4.3.1 Life cycle impact assessment of concrete in m^3

GaBi© ts 10.0 was used in this study. Especially in the discussion, we focus on climate change (GWP in kg CO_2e), in order to compare the current study with other previously published study results (Table 2). Further, AP and ADPf are of more intensive interest than other indicators, since these two midpoint indicators were also named in other studies (e.g., Stoiber et al. 2021). Additionally, we made use of the indicator CED (primary energy [MJ]).

Table 7 shows the impacts of C1–C9 in the reference flow of 1 m^3. With regard to climate change, it is visible that the modeled concretes show comparatively high impacts (reference values range between 232 and 618 kg CO_2e/m^3). Detailed statements can be made upon closer analysis:

Table 6 Abbreviations and legend for concrete and fiber

Abbreviation	Legend
C1	CEM I 42.5; 700 kg only Portland cement, less quartz sand
C2	CEM I 42.5; 550 kg Portland cement and quartz sand
C3	CEM I 42.5; 400 kg Portland cement, high proportion of quartz sand
C4	CEM III 42.5; 700 kg only cement, less quartz sand
C5	CEM I 52.5; sand (no quartz sand and no gravel)
C6	CEM I 52.5; high proportion of gravel
C7	CEM I 42.5; high proportion of gravel
C8	CEM I 42.5; lower proportion of gravel
C9	CEM I 52.5; high proportion of quartz sand and gravel
F1	Given impregnation; conventional energy use
F2	Given impregnation; optimized energy
F3	German fiber; EP impregnation
F4	Japanese fiber; EP impregnation
F5	SBR impregnation

Table 7 Life cycle impact assessment–concrete production in m^3 with grid mix (GWP color code: red = highest emissions, green = lowest emissions) (please check Supp. Material for concrete mixtures)

	CML2001 - Aug. 2016											
Concrete	**ADPe**	**ADPf**	**AP**	**EP**	**FAETP**	**GWP**	**HTTP**	**MAETP**	**ODP**	**POCP**	**TETP**	**CED**
C1 (CEM I 42.5)	1.4E-03	3,360	0.7	0.2	15.3	728	59.9	72,562	4.71E-06	0.06	0.907	4,723
C2 (CEM I 42.5)	1.1E-03	3,007	0.6	0.1	12.1	592	47.6	57,488	3.70E-06	0.05	0.757	4,147
C3 (CEM I 42.5)	1.0E-03	2,831	0.5	0.1	15.2	468	46.8	58,819	4.71E-06	0.04	0.687	3,885
C4 (CEM I 42.5)	1.4E-03	3,136	0.7	0.2	15.3	369	59.8	52,561	4.71E-06	0.04	0.870	4,432
C5 (CEM I 42.5)	5.8E-04	2,970	0.5	0.1	0.4	506	21.3	25,315	2.80E-09	0.02	0.564	4,165
C6 (CEM I 52.5)	6.1E-04	2,122	0.4	0.1	0.3	449	20.5	20,094	1.96E-09	0.01	0.517	2,839
C7 (BMK-D5-1)	8.7E-04	2,226	0.5	0.1	0.4	596	28.1	27,549	4.18E-09	0.02	0.617	3,044
C8 (BMK-D5-1)	9.9E-04	2,390	0.6	0.1	0.4	668	31.8	31,018	3.92E-09	0.03	0.683	3,285
C9 (BMK-D5-1)	9.9E-04	2,610	0.6	0.1	0.5	687	32.4	32,502	3.92E-09	0.04	0.701	3,680

C1–C5 are mixes explicitly developed for innovative processing methods (extrusion and 3D-printing), which can explain high impact values by laboratory standards. Irrespective of any concrete composition, cement has the largest share of the climate change impact with over 50% (see Figs. 2, 3, and 4). If the proportion of quartz sand is increased, CC as midpoint indicator also increases, but to a much lesser extent than with an increase in the proportion of cement. With regard to CC, it can be clearly stated that if the proportion of cement in kg (LCI) decreases, CC impact also decreases (LCIA). It is striking that C4 has the lowest impact in terms of CC (Table 7): from LCIA and LCI, it is evident that CEM I seem to have a far greater negative impact than CEM III (compare, for example, C4 vs. C1) (Figs. 2, 3, and 4).

Short digression: In addition to the CML methodology (e.g., Table 7), we performed another LCIA evaluation using the EF 3.0 methodology as an example. In general, the absolute values are about 1% higher than those of the CML evaluation. However, the composition of an impact indicator (e.g., climate change/global warming potential) is completely identical to the composition of the CML methodology (see also Figs. 2, 3, and 4). Consequently, the evaluations with other methodologies (in our case with EF 3.0) do not result in any new findings, except that the absolute emissions differ slightly, which can, however, also be represented by different scenarios (in our case different concretes or fibers), since there is not only one final concrete mix.

With regard to not only CC but also AP, ADPf, and CED, it can be concluded that a reduction of cement and an increase of sand have a positive effect on emissions. However, this must be viewed critically with regard to resource scarcity (Peduzzi 2014). In more detail, with regard to CC, it can be concluded that CEM 42.5 appears to have a slightly more positive impact than CEM 52.5. AP, analogous to CC, is mainly influenced by cement, whereby carboxymethyl cellulose also has a share of about 20% in total AP. With regard to ADPf, main drivers are much more homogeneous: cement accounts for about 1/3 of the emissions on average, PVA fibers accounting for about 20% of total ADPf, and fly ash and carboxymethyl cellulose are also contributing.

CED varied most markedly from mix to mix with its main drivers, and a blanket statement is less easy to make than for the indicators already mentioned: in most cases, cement is also the main driver, accounting for about 30% of total CED. For C5, however, silica sand also has a share of 27%. For

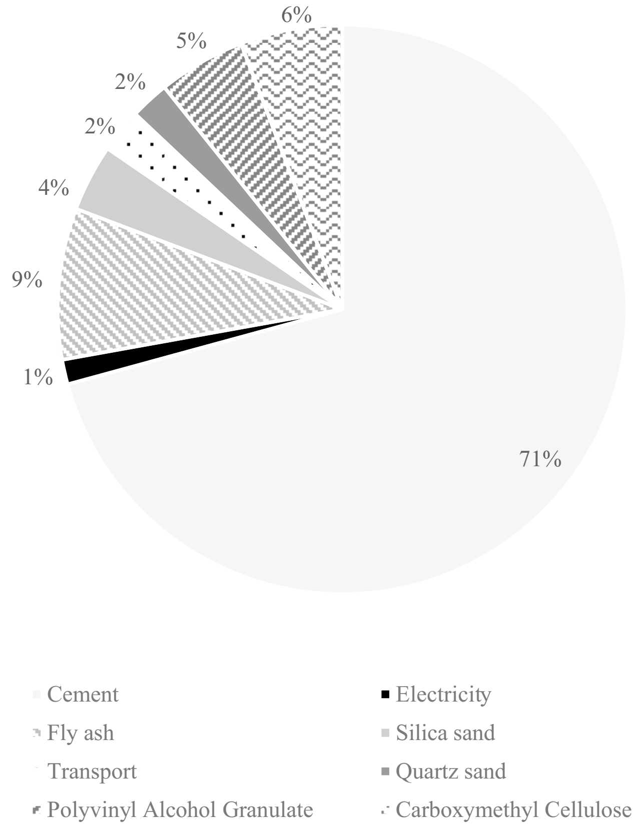

Fig. 2 Composition total climate change C1 (CEM I 42.5) — hotspots

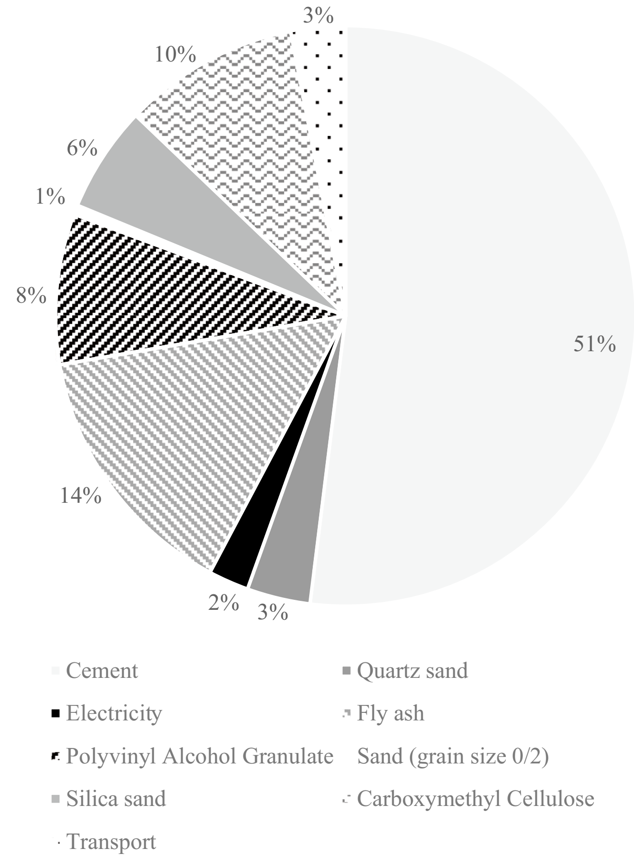

Fig. 3 Composition total climate change C4 (CEM III 42.5) — hotspots

C1 to C4, on the other hand, PVA fibers are more important (16–18% of total CED), as is carboxymethyl cellulose (13–18% of total CED). Transport and electricity account for significantly less than 4% of individual indicators and are thus to be regarded as negligible components in the concrete production and optimization processes.

Following as a short interim summary: the less mass of cement, the better the LCIA is; the more CEM III instead of CEM I, the better the emissions are. Transportation and energy are not the most relevant adjusting screws.

4.3.2 Life cycle impact assessment of fiber in kg

In the following, values for the cradle-to-gate production of 1 kg carbon fibers are shown. Both the black box models from the database (F1–F2) and the independently modeled models with assumed impregnation and energy (F3–F5) show comparable impact values (Table 8).

Table 8 shows that F1 (German fiber, coated with epoxy resin) has the highest impact for a number of indicators (e.g., ADPe, ADPf, AP, GWP, HTTP, MAETP, TETP, and CED). In terms of climate change (GWP in kg CO_2e), F2 represents mainly the lowest impact (also for ADPf, ODP, and CED). Comparing the CC values of F1–F5 with reference studies (Table 8), the current values are in the comparatively higher range, but still all within the range of reference values (references ranging from 11.4 to 31 kg CO_2e/kg (Table 8)).

As F1 and F2 are black box processes, no differentiation could be made between, e.g., impregnation and raw fiber. For this reason, we consider F3–F5 in the following in more detail: This analysis shows that carbon fiber production accounts for the largest share of all four indicators considered in more detail (GWP, AP, ADPf, and CED), regardless of whether production took place in Germany or Japan (F4 = Japan production). The percentage share of the respective total electricity impact (grid mix) needed for impregnation (not fiber production) did not exceed the normalized share of 3% for any fiber production and any indicator.

The SBR impregnation appears to have a lower percentage of effect than the EP impregnation. This becomes even more clear with the absolute values per kg fiber or per m^2 impregnation — shown in Table 9.

At this point, it should be noted that the choice of the coating material (SBR vs. EP) depends on the subsequent use. Therefore, an unrestricted choice between EP and SBR coatings is not always possible. EP impregnated

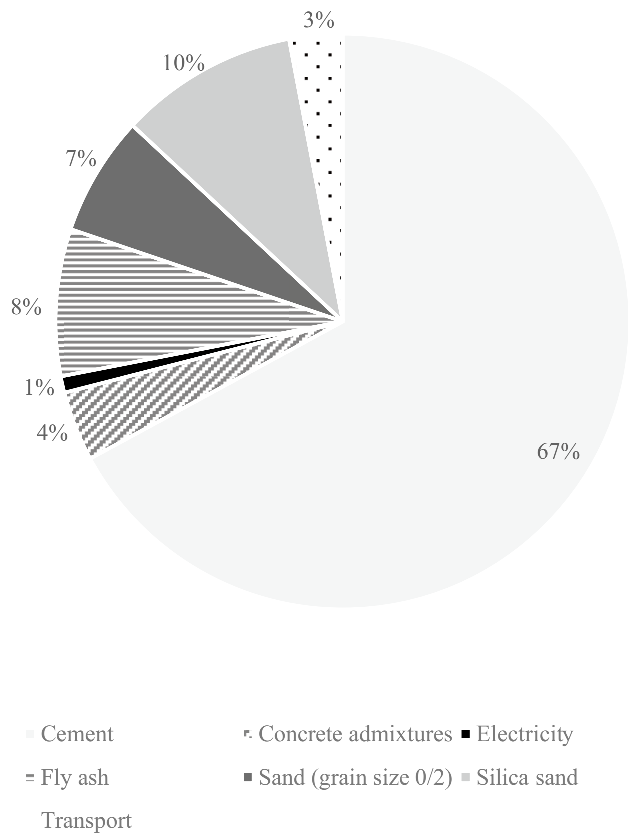

Fig. 4 Composition total climate change C5 (CEM I 52.5) — hotspots

reinforcements are characterized by stiff, brittle components, which are mostly used for conventional building compositions. SBR impregnated components, on the other hand, are characterized by soft, flexible reinforcements. This type of reinforcement is used for maintenance processes, such as retrofitting, e.g., in the form of lamellas for the maintenance of bridges or buildings. In addition, the use of SBR impregnated reinforcements is particularly suitable for the realization of filigree, thin, and curved components (Kortmann 2020). This brings us to the point that EP is better suited as an impregnation for our application case of the double wall. Furthermore, it should be noted at this point that both the assessment of EP and SBR are so-called black box processes in the databases, which have not been analyzed and reproduced in detail at this point and which should be investigated in a follow-up study. In addition, detailed considerations of the tensile strength are also missing at this point.

Especially the amount of energy needed seem to be crucial in fiber production — which can be said despite black box processes. Furthermore, in a follow-up study, these black box processes have to be broken down and also the impregnation has to be analyzed in detail to assess whether SBR still shows less emissions than EP impregnation from cradle-to-gate — including tensile strength. This will lead to detailed and more advanced statements. An initial insight into this is already provided in the "2.18" of the current study.

4.3.3 Life cycle impact assessment of double wall

Conclusive, the combination of impregnated carbon fibers (F1–F5) and concrete mixes (C1–C9) in the defined functional unit of a double wall was considered. In addition, a transport for each concrete (C1–C9) and fiber (F1–F5) of 100 km by lorry were assumed, as well as energy of 2.7 MJ according to Neuson (2021) for the compaction of the composite material. For the combination of fibers and concretes, the result range of GWP in kg CO_2e/double wall is between the baseline scenario of 754 kg CO_2e for C1 and F1 and the best scenario of 453 kg CO_2e for C4 and F2 (Table 10). The difference in CC in kg for an equivalent carbon fiber–reinforced double wall (used for same application) is therefore of significant 301 kg CO_2e. As shown in previous sub-chapter, both C4 and F2 represent the lowest CC values in their respective categories (concrete or fiber). C4 uses exclusively CEM III, and no CEM I, which seems to reduce emissions significantly. F2 is produced exclusively with optimized energy (black box), which leads to emission savings.

Similar differences are also evident in other impact categories, with the combination of fiber and concrete — not being equally optimal or bad in all indicators. Nevertheless, the combination of C1 and F1 always represents the worst scenario — for all midpoint indicators. This was already to be expected from the two preceding individual component evaluations.

For ADFf, the difference between the best- and worst-case scenarios is 1.829 MJ (Table 11), and for AP, the difference between the combination C1 and F1 (worst) and C6 and F3 (best) is 0.38 kg SO_2e (Table 12). C6 is largely the most positive concrete mix considered in this study, influenced by less cement and more sand use, while C1 is the most negative example. F1 is largely to be regarded as the most environmentally unfriendly fiber within the current framework. F2 is the most positive fiber concerning environmental emissions.

4.4 Interpretation

Following, we set the objective of the study and compare CRC with SRC. Furthermore, we consider hotspots in detail as part of a sensitivity analysis.

Table 8 Life cycle impact assessment–Carbon fiber production in kg with grid mix (GWP color code: red = highest emissions, green = lowest emissions)

	CML2001 - Aug. 2016											
Fiber	**ADPe**	**ADPf**	**AP**	**EP**	**FAETP**	**GWP**	**HTTP**	**MAETP**	**ODP**	**POCP**	**TETP**	**CED**
F1	1.3E-05	447	0.05	0.01	0.06	28	1.1	1,940	3.2E-13	4.9E-03	0.04	575
F2	1.1E-05	343	0.04	0.01	0.05	20	0.7	1,195	2.7E-13	3.7E-03	0.03	433
F3	1.2E-05	399	0.04	0.01	0.06	26	0.7	1,375	5.7E-13	3.8E-03	0.04	551
F4	1.0E-05	441	0.04	0.01	0.05	27	0.6	960	4.4E-13	4.2E-03	0.03	539
F5	5.7E-06	409	0.05	0.01	0.06	25	1.0	1,785	6.8E-11	4.5E-03	0.02	525

Table 9 Absolute indicator results for impregnation: EP vs. SBR

	CML2001 — Aug. 2016 — impregnation (0.11 kg/m^2)			
Impregnation	GWP	AP	ADPf	CED
F3 EP	1.5	1.6E-03	29.9	36.5
F4 EP	1.5	1.6E-03	29.9	36.5
F5 SBR	0.8	2.0E-03	21.1	23.9

Table 10 Climate change for CRC double wall, all scenarios (color code: red = highest emissions, green = lowest emissions)

	Climate Change: GWP 100 years [kg CO_2 eq.]								
	innovative: extrusion, 3D-print					known casting method			
Fiber \ Concrete	C1	C2	C3	C4	C5	C6	C7	C8	C9
F1	**754**	670	592	530	609	556	641	689	700
F2	678	593	516	**453**	533	479	564	613	623
F3	736	651	574	511	591	537	622	671	681
F4	750	666	588	526	605	552	637	685	696
F5	730	646	568	506	585	532	617	665	676

Table 11 ADPf for CRC double wall, all scenarios (color code: red = highest emissions, green = lowest emissions)

	ADP fossil [MJ]								
	innovative: extrusion, 3D-print					known casting method			
Fiber \ Concrete	C1	C2	C3	C4	C5	C6	C7	C8	C9
F1	**6,775**	6,563	6,466	6,680	6,513	5,890	5,943	6,061	6,190
F2	5,730	5,519	5,421	5,635	5,469	**4,846**	4,898	5,017	5,145
F3	6,291	6,080	5,982	6,196	6,030	5,407	5,460	5,578	5,707
F4	6,709	6,498	6,400	6,614	6,448	5,825	5,877	5,996	6,124
F5	6,395	6,183	6,086	6,300	6,134	5,511	5,563	5,682	5,810

4.4.1 Comparison

To meet the objective of the current study, the interest arose whether the cradle-to-gate emissions of a CRC double wall are lower, and if so by how much, than an equally functional SRC double wall. To focus on the comparison of CRC vs. SRC, the best- and worst-case (baseline) scenarios were selected, both with grid mix electricity input. In order to ensure the same function of the differently reinforced double walls, the mass flows based on the data given by Otto and Adam (2019) were chosen (Table 3). CRC (double wall) requires 1.43 t of concrete and 10.2 kg of fiber reinforcement per double wall, while SRC (double wall) requires 2.63 t of concrete and 231 kg of steel reinforcement. The same transport distances have been assumed for the CRC scenarios and the usage of grid mix energy for mixing and compacting, scaled according to masses (SRC > CRC). For the sake of simplicity and replicability, an identical composition of concrete (C1 and C4 (best and worst CC results)) — varying only concrete-masses (2.63 t of concrete) — has been assumed. For modeling SRC, we exchanged F1–F5 with three different steel values (Table 2 (only reported as CC)): (1) a previously selected Ecoinvent steel process *GLO: market for reinforcing steel*. This process was chosen because it is explicitly described as a reinforcing steel and CC per kg of final product produced is around 2.1 kg CO_2e/kg — which is comparable to previous studies (Backes et al. 2021; Burchart-Korol 2013; Suer et al. 2021). In this case, it was possible to show more indicators than just CC, as the full CML methodology is evaluated (Table 13), as we could make use of the process; (2) the value assessed by Gomes et al. (2013) for steel produced within an EAF (Table 2; 0.61 kg CO_2e/kg steel); and (3) the value assessed and published by Suer et al. (2022), as they focus on H_2 and direct reduction in steel production (Table 2; 0.78 kg CO_2e/kg steel). All comparison models were balanced with

Table 12 AP for CRC double wall, all scenarios (color code: red = highest emissions, green = lowest emissions)

	AP [kg SO_2 eq.]								
	innovative: extrusion, 3D-print					known casting method			
Fiber \ Concrete	C1	C2	C3	C4	C5	C6	C7	C8	C9
F1	**1.05**	0.97	0.93	1.01	0.87	0.81	0.88	0.91	0.93
F2	0.9	0.82	0.79	0.86	0.73	0.67	0.73	0.77	0.79
F3	0.91	0.83	0.79	0.87	0.74	**0.67**	0.74	0.78	0.8
F4	0.95	0.87	0.83	0.91	0.78	0.71	0.78	0.81	0.83
F5	1.02	0.94	0.9	0.98	0.85	0.78	0.85	0.88	0.91

the grid mix energy source (average country electricity supply; this is a combination of hard coal, lignite, coal gases, natural gas, heavy fuel oil, biomass, and biogas). Both, SRC and CRC, could be partly better placed in their results if a renewable electricity mix would be fed in, as shown in the following "2.18."

Figure 5 shows that a carbon-reinforced double wall (Otto and Adam 2019) has lower cradle-to-gate emissions in a direct comparison than an equally functional steel-reinforced double wall, but only when using the same concrete mix (C1 vs. C4) — e.g., SRC conv. (1369 kg CO_2e/double wall) vs. CRC (C1/F1) worst (754 kg CO_2e/double wall). SRC may well show lower emissions per double wall if the steel-reinforced concrete is coated with CEM III, while the CRC is coated with CEM I concrete (for example: CRC (C1/F1) worst 754 kg CO_2e vs. SRC EAF (C4) 611 kg CO_2e or SRC H_2 (C4) 650 kg CO_2e) (Fig. 5).

It is clear that emissions from the double wall can further be reduced if steel is not produced via the classic basic oxygen steelmaking route, but via newer technologies (EAF and H_2 + direct reduction) (Fig. 5: SRC conv. vs. SRC EAF vs. SRC H_2). The results would be similar, if we think about the use of recycled steel melted with conservative grid mix (mix of hard coal, lignite, coal gases, natural gas, heavy fuel oil, biomass, and biogas), where the values per kilogram of product are for example defined as 0.74 kg CO_2e (Neugebauer and Finkbeiner 2012), 0.77 kg CO_2e (Burchart-Korol 2013), or 0.4 kg CO_2e (Gabi© database, process DE: EAF Steel/Billet/Bloom).

Focusing at all other indicators, except climate change, using the *GLO: market for reinforcing steel process* (the other studies mentioned only give CC respective GWP in kg CO_2e, so a comparison is not possible), it becomes clear that reinforced concrete with blast furnace steel production performs worse than carbon-reinforced concrete — in all 11 CML midpoint indicators (exemplified by baseline (base.) scenario C1/F1 and C4/F2 (best case)) (Table 13).

Take home message: With an identical concrete mix (as, e.g., C1 or C4), CRC represents the alternative with the lowest emissions in form and function of a double wall. Nevertheless, carbon concrete is not generally more sustainable or, to put it in more detail, lower in kg CO_2e per double wall.

To answer whether the double wall (FU) should be built of SRC or CRC, in terms of its sustainability performance. The following can be said: According to the Climate Change values (Fig. 5), there is no clear answer to this question, but it is clear that there are no obvious CC advantages for CRC in the form and function of a double wall. At this point, the focus of sustainability should be extended to further indicators (as partly done in Table 13 for conv. steel production) and all three dimensions (added economic and social) in order to answer the question comprehensively.

4.4.2 Sensitivity analysis

Energy mix.

As additional sensitivity analyses, we considered as first for all processes and sub-processes (except black box processes (see inventory for energies used)) the use of a renewable energy mix for Germany instead of the originally used grid mix (DE: electricity grid mix (Sphera), reference year: 2017–2023: average German electricity supply; this is a combination of hard coal, lignite, coal gases, natural gas, heavy fuel oil, biomass, and biogas). The composition of the renewable electricity mix (own model, including, e.g., wind power, photovoltaic, hydropower, geothermal, biomass, and biogas) is based on the source of the federal environment agency in Germany (Umweltbundesamt 2021) and represents the composition of renewable electricity sources for 2020, which we modeled and used accordingly in GaBi© for concrete mixing and compaction. In the following, we will only consider the combination of C1 and F1 (concrete production and fiber production also modeled with this renewable energy mix) because it represents the worst-case scenario in all impact categories. The evaluation of only concrete production shows that the use of renewable energies in concrete production (scenario C1 and F1) has only a minor positive effect on the production of a CRC double wall (about 1% improvement) (Table 14).

With this evaluation, it becomes clear that the use of renewable energies in concrete mixing and compaction has little influence on the total emissions (no renewable energies were considered in fiber production), as already explained, the quantity of cement itself and the cement selection have a much greater influence.

Table 13 Eleven midpoint indicators for SRC and CRC in comparison, CML2001-Aug.2016 (GWP color code: red = highest emissions, green = lowest emissions)

	ADPe	ADPf	AP	EP	FAETP	GWP	HTP	MAETP	ODP	POCP	TETP
SRC conv. (C1)	0.0	10,911	3.1	1.4	384.2	1,369	1,009	830,699	0.0	0.5	21.5
SRC conv. (C4)	0.0	10,735	3.0	1.4	384.7	954	1,010	808,492	0.0	0.5	21.5
CRC (C1/F1)(base.)	0.0	6,775	1.0	0.2	10.5	754	49	66,036	0.0	0.1	1.0
CRC (C4/F2)	0.0	5,635	0.9	0.2	10.6	453	46	46,597	0.0	0.0	0.9

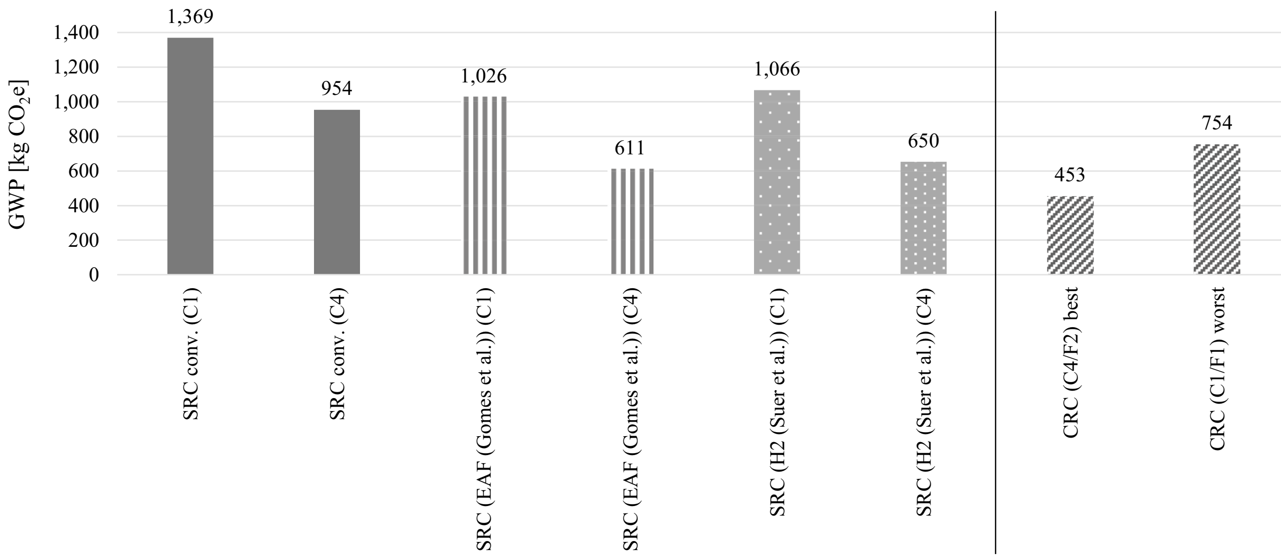

Fig. 5 Comparison: cradle-to-gate SRC vs. CRC double wall climate change emissions

Table 14 Sensitivity analysis: renewable energy mix for concrete production and compaction in a double wall

C1/F1	Indicator							
	GWP	ADPf	AP	ADPe	EP	ODP	POCP	HTP
Renewable mix	743	6,676	1.05	1.04E-03	0.19	2.0E-06	7.0E-02	49
Grid mix	754	6,775	1.05	1.04E-03	0.19	3.0E-06	7.0E-02	49
Improvement in %	−1%	−1%	0%	0%	0%	−33%	0%	0%

Energy mix in fiber production — first approach according to literature.

In order to estimate the energy use for raw fiber production itself — despite secondary data for fiber production and partly used black box models, Das (2011) was selected as reference for the sensitivity analysis. Das (2011) differentiated in electrical and thermal energy to be needed for the production of 1 kg fiber, starting from PAN (Das 2011): 72.22 MJ/kg electrical energy and 97.69 MJ/kg thermal energy were assumed (Das 2011; Hohmann 2019). Balancing corresponding MJ-data with the compiled renewable energy mix according to the federal environmental agency (Umweltbundesamt 2021) and biogas; and comparing this with grid mix energy sources, it is visible that the production of 1 kg of impregnated fiber is conditionally better or worse compared to grid mix energy use — depending on which midpoint indicator is of interest: GWP and ADPf improve with steady use of renewable sources. AP and CED, however, vary or become steadily worse in their impact for the same size of reference flow of 1 kg of produced fiber (Table 15).

From this brief evaluation, it is not only clear that different interests in impact indicators generate different results, but it is also clear that the energy used in fiber production accounts for a considerable share.

Table 9 shows, among others, the climate change values for the production of 1 kg of impregnated fiber. F2, for example, resulted in a CC per kg of fibers produced of 20 kg CO_2e (Table 9). Applying the MJ-values defined by Das (2011), the share of grid mix energy sources in CC is 89% for F2 (17.3 kg CO_2e in absolute terms, see Table 15). If electricity alone was to be switched to renewable sources in fiber production, CC for F2 in kg would drop from 20 to 11.9 kg CO_2e/kg, which represents an improvement of

Table 15 Sensitivity analysis: renewable energy mix and biogas for 1 kg fiber production

Energies	Indicator			
	GWP [kg CO_2e]	ADPf [MJ]	AP [kg SO_2e]	CED [MJ]
Grid mix electricity/grid mix thermal energy	17.3	225.2	1.68E-02	264.8
Renewable electricity/grid mix thermal energy	9.1	125.5	1.56E-02	391.3
Renewable electricity/renewable thermal energy	5.2	20.3	5.59E-02	546.4

Table 16 Sensitivity analysis: cement being substituted by clay and limestone — emission per m^3

	CML2001 - Aug. 2016											
Concrete	**ADPe**	**ADPf**	**AP**	**EP**	**FAETP**	**GWP**	**HTTP**	**MAETP**	**ODP**	**POCP**	**TETP**	**CED**
C1	1.4E-03	3,360	0.7	0.2	15.3	728	59.9	72,562	4.71E-06	0.06	0.907	4,723
C1 - clay	1.0E-03	2,020	0.6	0.1	15.2	526	47.4	60,700	4.71E-06	0.04	0.693	4,160

40%, purely through the purchase of a renewable electricity mix. If, in addition, the thermal energy would be switched to biogas, CC of F2 would further be reduced to 7.9 kg CO_2e/kg, compared to original 20 kg CO_2e/kg — this would correspond to a CC reduction of approx. 60% for the production and impregnation of 1 kg carbon fiber. Despite these strongly positive effects of the use of renewable energies, it should again be noted that the consideration and appropriate selection of the respective midpoint indicator is important (Backes and Traverso 2021b).

From this brief digression, it quickly becomes clear that the use of renewable energy sources is irrelevant for concrete production and mixing, as hardly any improvements in emissions can be achieved. However, since the concrete can also be used for steel-reinforced concrete and not only for carbon-reinforced concrete, a statement on whether CRC is "better" for the climate targets than SRC cannot be made in the context of the consideration of renewable energy sources and concrete production — without taking the fibers into account. However, the situation is different for fiber production: we have assumed here that theoretically, the entire fiber could be produced in Germany using the German renewable electricity mix — this, as shown, would lead to an improvement in parts of the midpoint indicators (and by this also partly improving climate targets). However, besides the USA and Europe, Japan is also one of the main producers of carbon fibers. Following the European Union, three Asian economies have recently announced targets for achieving net zero emissions: which includes Japan by 2050, South Korea by 2050, and China by 2060. While it is too early to assess the impact of these statements, the stated ambitions will most likely further accelerate the deployment of renewable energy across all sectors, with potentially significant implications for global (fiber) markets (International Energy Agency 2020). The assumption that all of fibers can be produced with renewable energies may be achieved somewhat sooner in Europe than in Japan, but in both cases, it should be regarded as an extremely positive scenario, since we have so far only been thinking of laboratory scales and not of large-scale industrial batches. Currently, related to this study and thus to the SRC or CRC double wall component, CRC is not aid in pursuing policy goals to address climate change.

Concrete mix — focusing on cement substitutes Since the concrete mix or, more precisely, the cement has a prominent share in the emissions, we focus in a further sensitivity analysis on the theoretical use of clay to substitute cement components. This is a first approach of possible substitutes, which has to be considered in more detail in further research; nevertheless, we provide an insight by this consideration: Our C1 concrete mix (baseline) has a proportion of 700 kg of CEM I 42.5 R cement (see Supp. Material). If we now theoretically replace 35% of this CEM I 42.5 R cement with limestone and a larger proportion of clay (also done practically in laboratory), the absolute proportion of CEM I is reduced (Avet 2017; Zunino Sommariva 2020; Sharma et al. 2021) — and with it the total emissions per m^3 of concrete (Table 16).

Partial substitution may consequently lead to lower emissions (e.g., Table 16: 526 kg CO_2e vs. 728 kg CO_2e per m^3), but it should also be noted that the emissions of C1 with the use of clay and limestone are still partly higher than those of the C4 (CEM III) mix (e.g., in GWP: C4: 369 kg CO_2e vs. 526 kg CO_2e/m^3).

5 Limitations and future outlook

A detailed modeling of CRC with nine different concrete mixes and five different fiber variants and impregnations was performed, resulting in 45 different scenarios for a reinforced double wall — C1 and F1 representing the baseline scenario (highest emissions). Detailed and reproducible life cycle inventories are available and thus allow for global optimization and post-modeling. The inventories could finally be compared with an equally functional steel-reinforced double wall. The results not only are plausible (compared to Table 1) and of relevance but also require further investigations: The current study is limited by the combination of primary and secondary data use (e.g., concrete (primary data) vs. fiber (secondary data)). In a future study, primary data on fiber production and impregnation would be of great advantage. Currently, carbon-reinforced concrete components are often still laboratory-scale compositions, and the feasibility and mechanical properties of most combinations are as yet unknown/untested. Within this study, we did not assess wall insulation (insulation material or concrete) and connection between the two walls (composite grid), which will increase the total emission in future studies. In conclusion, we assumed that the exact identical concrete composition can be used with any reinforcement. Additionally, we only focused on the production of our FU (double wall), not considering the use phase and even more important the end-of-life. This needs to be further differentiated and assessed — as shown in Backes et al. (2022a, b) and Hatzfeld et al. (2022). The use phase as well as EoL would have gone beyond the scope of the current publication, which is why various publications from the life stages, always with the identical FU (double wall), have been implemented. The results on EoL show that mechanical recycling of carbon fibers is overall the route with the lowest energy input and emissions. However, compared to pyrolysis, the recycled carbon fibers from mechanical recycling have lower quality. Therefore, despite the higher energy input, pyrolysis is a more promising approach to closing the material loop. In addition, concrete with recycled aggregate can reduce emissions by a quarter compared to primary concrete. In general, however, the continued life of reinforcement is hardly comparable. Steel can be recycled with almost no losses or downcycling, while a closed loop of carbon fibers is not yet possible. Therefore, the properties of carbon fibers and the EoL processes need to be improved to achieve a closed loop with optimized environmental performance (Backes et al. 2022a, b).

Further limitations should be optimized in subsequent studies, where especially fibers and their coatings are of particular relevance, and innovations such as the increased incorporation of clay (Urban and deutschlandfunk.de 2020) into concrete might be of further research and practical interest. In particular, the tensile strength, respectively the different impregnations (EP vs. SBR), need to be further investigated, as EP and SBR provide different stiffness; only the fiber base of PAN (polyacrylonitrile) has been investigated in this study; innovative materials such as a PE (polyethylene) base or even glass fiber as reinforcement have not yet been considered. The fiber base as well as the impregnation itself is crucial for not only the construction but also the emission backpack (Backes et al. 2022c). It is now necessary to maintain the function of the fibers but possibly to reduce their mass or to define alternatives for the carbon fiber since these have a relevant and currently not optimizable share in the total emissions of a double wall.

With regard to the question of whether it would be better to build the double wall from SRC or CRC from an environmental sustainability perspective, it is not possible to answer this question on the basis of climate change, since neither of the two options represents a clear improvement: If steel is produced by hydrogen or EAF, the CC emissions are comparable to those of CRC and not significantly increased. CRC for sure requires less material (resource saving).

5.1 Future outlook

Apart from the environmental aspect of sustainability, the choice of CRC or SRC for the double wall obviously needs to be broadened to focus on the other two dimensions of sustainability: LCC (life cycle costing) (cost/economic) and S-LCA (social life cycle assessment) (social). In future, this environmental assessment should be placed in the context of a LCSA. The reason for naming the LCSA at this point is that strong changes are expected, especially in the social sector (S-LCA), with the introduction of CRC at an industrial scale. CRC is already being 3D-printed (e.g., Mechtcherine et al. 2020 and Neef et al. 2020) or extruded (e.g., Kalthoff et al. 2022) at laboratory scales — which can significantly change the world of work in the construction industry. Furthermore, the fibers are largely sourced from Asia and the USA, which implies different social factors than pure production steps in Germany or the EU. In terms of cost, CRC will exceed SRC, making it questionable what impact economics will have in the long run in this three-dimensional construct, especially in contrast to the environmental dimension (LCA).

Recycling of this new type of composite material in particular may still present us with future challenges. Summarizing current findings on the end-of-life phase of textile-reinforced concrete, it is clear that downcycling due to damage to the textiles is unavoidable. A second reuse of the reinforcement textile in its original purpose can be excluded with current methods (Backes et al. 2022a, b; Kimm 2019; Kimm et al. 2020). In the future, the construction method itself and the component, i.e., our FU of a double wall, for the carbon-reinforced concrete will also have to be questioned. A double wall is not the optimal component in terms of emissions for the CRC, as shown in our results. At this point, cooperation with civil engineers is once again needed to design innovative constructions that make the CRC useful also in terms of emissions and not only in terms of resource savings and thus can seriously replace steel-reinforced concrete in some places.

6 Conclusion

The aim of this article was to assess the environmental performance of a CRC double wall and compare its performance with a SRC double wall, with help of a LCA. Both double walls have the same function in reality. Forty-five CRC LCA scenarios, varying concrete mixes and fiber reinforcements, have been assessed — to identify hotspots, to show optimization potential, and to support decisions on choosing CRC or SRC as sustainable composite material.

For the cradle-to-gate LCAs (in GaBi© 10.0), both primary and secondary data were used. The functional unit of the composite material was set to a double wall, reference flows in 1 m^3 for nine concrete mixes and 1 kg for five fiber variants were individually balanced. Insulation material, connecting pins, and specific transport routes (all set to 100 km) were not considered. Eleven CML midpoint indicators and the CED were assessed and analyzed.

For the sustainability performance of concrete (in 1 m^3), the direct comparison reveals CEM III (0.3 kg CO_2e/kg) to be beneficial to CEM I (0.8 kg CO_2e/kg) with regard to its emission load. The substitution of 35% of CEM I with clay is further advantageous (~27% less climate change emission). The use of renewable energy in mixing and compacting the concrete has little impact on the overall concrete emissions. For fibers, SBR has an advantage over EP impregnation. If renewable energy would be used for fiber production and impregnation, an emission reduction of up to 60% might be possible.

Even though less raw material is required for CRC, it does not represent a clear advantage in terms of sustainability performance (emission) over SRC in the function of a double wall, focusing on climate change. If recycled steel or steel from EAF production would be used, the concrete mix is the decisive control variable. A combination of EAF steel and CEM III results in a lower climate change (611 kg CO_2e/double wall) than conventionally produced fibers (no optimized energy and a grid mix energy mix) embedded in CEM I (754 kg CO_2e/double wall).

In future research, fiber production and impregnation in particular need to be studied in detail (largely black box processes — other/additional databases as, e.g., Ecoinvent, might provide more transparency), the influence of substitutes such as clay, and since in terms of environmental sustainability performance neither wall (SRC vs. CRC) is better off, new and innovative building components need to be established and the two other pillars of sustainability (economic and social — LCSA) need to be considered.

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Declarations

Conflict of interest The authors declare no competing interests.

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