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Building Sector Issues in about 100 Years: End-Of-Life Scenarios of Carbon-Reinforced Concrete Presented in the Context of a Life Cycle Assessment, Focusing the Carbon Footprint

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Abstract: Carbon-reinforced concrete (CRC) has the potential to play a pivotal role in optimizing the built environment and has therefore been experiencing a wave of research and development in the construction industry in recent years. The production of carbon fibers for CRC is energy-intensive, prompting the need to explore circular economy approaches (e.g., recycling at the End-of-Life (EoL)) to optimize the environmental performance of this material. Underdeveloped processes and a resulting lack of primary data regarding the recycling of CRC have hampered a comprehensive sustainability assessment of the novel composite building material. The novelty of this article is the detailed presentation of possible EoL scenarios for CRC and the detailed determination of the respective environmental impacts. This study aims to model EoL options within a Life Cycle Assessment (LCA), focusing on the EoL stage based on ISO 14040/44 using the GaBi ts 10.5.1.124 software and the CML2001 (2016) methodology. The practical relevance of the study lies in the early consideration of the entire life cycle of new materials, such as CRC, already in the design phase. Furthermore, the EoL can have relevant impacts on the environment, and due to an increasing significance of sustainability aspects, this LCA clarifies first approaches for the future of the construction sector in quantitative statements (e.g., CO_2 emissions). All data are literature-based and are explained in detail and calculated for our case study with the functional unit of one kilogram of re-usable material (reusable and fully usable “raw” material for further use/ development) from a double wall. The impact assessment was calculated for 11 midpoint categories and related indicators, although the main focus was on Global Warming Potential (GWP). It was found that the highest-quality recycled options for CRC arise when the individual fractions (concrete matrix and carbon fibers) are first broken up, separated and then individually processed. This study focused mainly on the processing of the carbon fibers contained in CRC, for which pyrolysis and mechanical recycling have the strongest potential for industrial application. For the demolition and separation of both the concrete and the carbon fiber fractions, the conventional transport from the demolition site to the stationary processing plant proved to be the main driver of the GWP (1.4×10^{-3} kg CO_2e). In the subsequent processing of the carbon fibers, pyrolysis showed a higher GWP (9.7×10^{-3} kg CO_2e) than mechanical recycling (3.1×10^{-4} kg CO_2e). In addition, the production of one m^3 of concrete (C30/37) was compared to a primary raw material concrete fraction. Concrete can be successfully used as a substitute material for the gravel present in the C30/37 concrete. The use of recycled parts in concrete (originating from the concrete used in carbon-reinforced concrete) as a substitute for primary gravel showed a savings of 6.9 kg CO_2e per m^3 of primary concrete, corresponding to a reduction of 22.5%. The results show that the 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 a lower quality. Therefore, despite the higher energy input,

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pyrolysis is a more promising approach to close the material cycle. Furthermore, recycled aggregate concrete can reduce emissions by a quarter compared to primary concrete. Finally, this work aimed to provide a basis for further life cycle optimization in the construction sector. In subsequent studies, the EoL must be combined with the production and use stages to depict the entire life cycle, identify possible trade-offs and compare the results with conventional construction methods or materials such as steel-reinforced concrete.

Keywords: carbon-reinforced concrete; LCA; end-of-life; recycling; carbon fiber; reinforced concrete

1. Introduction

The construction sector is an important part of the fight against climate change. Current data show that globally, 37% of energy-related CO_2 emissions (incl. use stage), about 7–8% of total CO_2 emissions (excl. use stage), 36% of energy consumption and 40% of raw material consumption are attributable to the construction sector [1–3]. Accordingly, there is an increasing focus on sustainable design and resource-efficient use of building materials [4]. In this context, concrete is the dominant building material, with an estimated global consumption of 8.8 billion tons per year, which is under increasing criticism due to its resource consumption and production-related CO_2 emissions [5–7]. At the same time, both global population growth and urbanization are leading to an increased demand for housing and infrastructure, resulting in increased resource use as well as CO_2 release throughout a building's life cycle [4,8]. Therefore, to counter both a future threat of resource scarcity and increasing CO_2 emissions in the building and construction sector, sustainable innovations are needed to improve potential building sector issues in about 100 years [8–11].

The composite material carbon-reinforced concrete (CRC) has the potential to play a crucial role in optimizing the built environment [8,10]. CRC consists of reinforcement made of carbon fibers and thus substitutes the steel reinforcement of conventional steel-reinforced concrete, which has been the most widely used building material worldwide to date [12–14]. Steel reinforcement has the decisive disadvantage of being susceptible to corrosion—an additional concrete cover serving as corrosion protection is required [8]. In comparison, the carbon reinforcement found in CRC is non-corrosive, which could lead to thinner components and enormous concrete savings as well as ultimately an increase in environmental and economic efficiency [8,12,14]. CRC not only offers the advantage of not corroding but also has an above-average service life of an estimated 100 years [15], which is significantly longer than the service life of reinforced concrete (40–80 years) [8,12,14]. Furthermore, most studies in the construction industry focus on a service life of only 50 years [16,17], which can be exceeded by CRC and by this postpone (emissions) end-of-life challenges to in about 100 years (instead of 50 years).

Currently, End-of-Life (EoL) processes for CRC are underdeveloped and far from ideal from an environmental perspective. These processes lead to downcycling, which is insufficient to significantly reduce resource consumption and associated emissions within a circular economy [4,10]. Moreover, there is a lack of primary data on the recycling of CRC, which until now has hindered a complete sustainability assessment of this innovative composite building material. Developing a suitable reuse and recycling concept for CRC is critical for its environmental sustainability [10]. Consequently, this study aims to identify the currently possible methods for the CRC recycling and determine the associated energy consumption to enable an environmental assessment of CRC at the end of its life cycle. For this purpose, a Life Cycle Assessment (LCA) of the CRC at the end of its service life is carried out.

In the following, we present the State-of-the-Art of CRC and previous LCAs related to CRC. Furthermore, the LCA case study is split into two scenarios: mechanical recycling and pyrolysis. Both scenarios start with identical deconstruction, and it is assumed that the analyzed material is composed of primary raw material. Finally, we assume concrete to be reused in road construction as a possible second life scenario.

Carbon-Reinforced Concrete

CRC is an innovative composite building material composed of concrete and reinforcement which, in contrast to reinforced concrete, is not made of steel but carbon fibers [8]. In the construction sector, the starting material for the production of carbon fibers is polyacrylonitrile (PAN), obtained from petroleum. The fiber is impregnated and absorbs a predetermined amount of impregnation and water. Depending on the desired stability and flexibility of the reinforcing mesh, the construction industry usually distinguishes between two types of impregnation: epoxy resin (duromers; EP) or styrene-butadiene rubber (elastomers; SBR). To produce the reinforcement, up to 50,000 filaments (individual fibers) are bundled into long fibers and then spun into a roving (yarn) [12].

2. Recycling of CRC

When recycling CRC, a distinction is made between two routes. In the first, the demolition material is separated into individual fractions (concrete matrix and carbon reinforcement) that can be reused individually, and in the second route, the demolition material is not separated into individual fractions, resulting in the recycling of a heterogeneous and non-pure material [12]. Demolition and separation of the CRC components are expected to achieve the highest quality recycling output of the processed raw materials (processed concrete and processed carbon fibers) [12]. For this reason, only this type of recycling is considered in this study. The process for the CRC recycling elaborated by Kortmann (2020a) was used in this study as a model for the LCA. Figure 1 shows a sketch of the modeled and calculated processes.

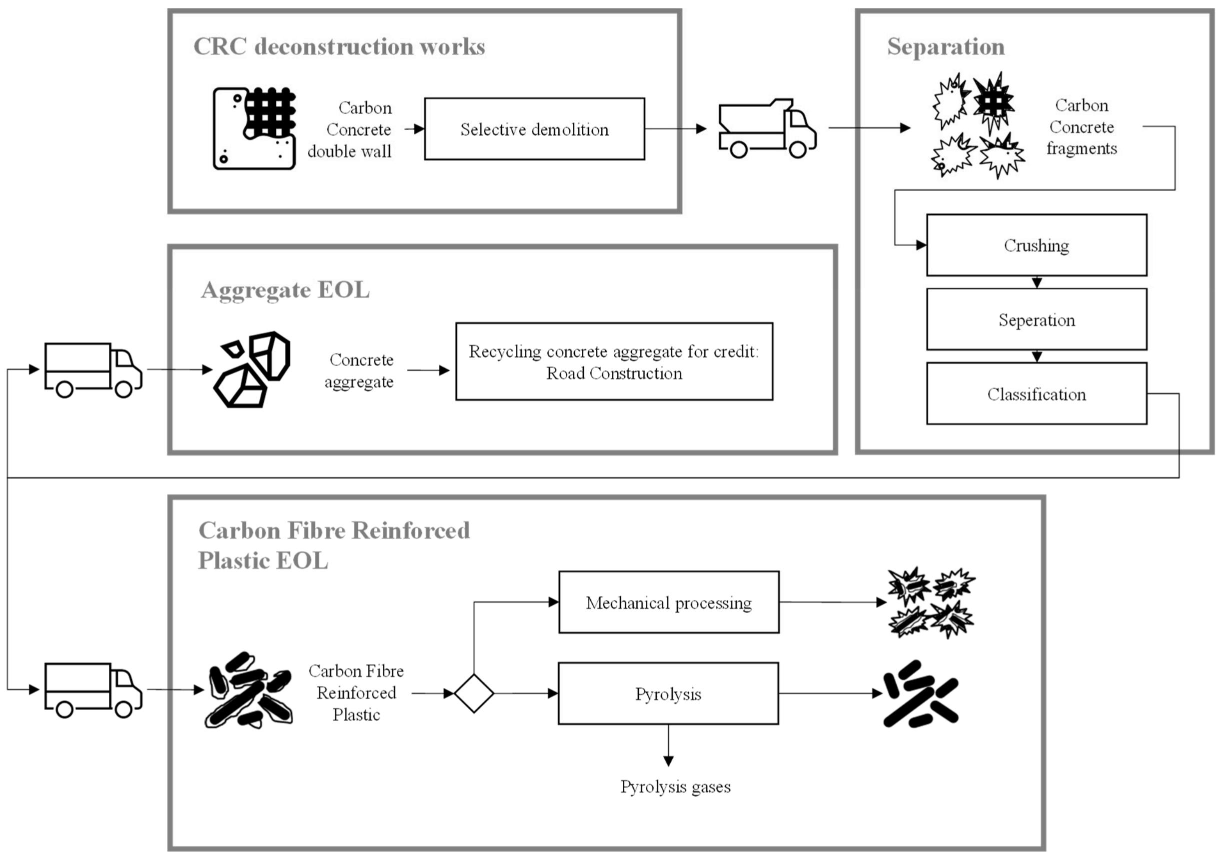

Figure 1. Processes to recycle CRC.

First, the CRC is selectively crushed using a carrier with attachment tools (concrete pulverizer and sorting grab). This steps results in pre-crushed, coarser fragments of CRC, where the carbon reinforcement is still present [12]. To separate the reinforcement and continue the preparation process, the pre-crushed CRC is loaded onto a dump truck using a hydraulic excavator and transported to a stationary preparation plant [12]. In the plant, the main crushing of the demolition material is performed by a jaw crusher (or an impact crusher), resulting in a heterogeneous mixture of building materials. This construction material mixture consists of concrete fragments of the grain group 0/56 and exposed carbon roving fragments with an average individual length of 80 mm. In this sub-process, the degree of disintegration of the carbon roving fragments from the concrete matrix is over 99% [12].

In the pre-separation, metallic embedded parts are first removed from the material flow by a stationary magnetic separator. Then, concrete fines (largest grain size of 2 mm), lightweight plastic components (e.g., spacers) and carbon reinforcement with a mass fraction of an estimated 10% are removed by a cross-flow classifier. In addition, the spacers and the carbon reinforcement are separated from the concrete fines by screening, which prepares them for further material recycling steps. The metallic components separated by the magnetic separator are sent to steel scrap recycling. After completing the pre-separation, the material stream contains a heterogeneous accumulation of concrete fragments of grain group 3/56 and exposed carbon roving fragments (average length 80 mm) [12].

A camera-based sorting unit is then used for the main separation of the concrete and carbon roving fragments. According to Kortmann, 97.7% of the carbon roving fragments can be separated in practice with this type of single-grain sorting. A maximum proportion of 2.3% of the carbon reinforcement remains in the concrete recyclate and finally reduces the mass fraction of the reinforcement structures from the former 1% to 0.023%. The result of the main separation is thus, on the one hand, the concrete fraction of grain group 3/56 (Aggregate EoL) with a residual carbon fiber content of less than 0.05% and, on the other hand, the separated carbon fiber fraction, including foreign mineral constituents of grain group 0/2. [12] Subsequent screening with a screen diameter of 3 mm allows the carbon fiber fraction to be separated from the foreign mineral constituents in a pure state, to obtain only the fibers themselves [12] (Figure 1). Next, a further fiber processing step, such as mechanical recycling or pyrolysis, follows.

2.1. Recycling of Carbon Fiber Composites

The three main waste management strategies for carbon fibers are (1) landfilling, (2) energy recovery in the form of incineration or co-incineration in a cement kiln [18,19], and (3) recycling [20–22]. Since this study focuses exclusively on carbon fiber recycling, landfilling and energy recovery are not considered. Carbon fiber reinforced plastics (CFRP) waste is currently not suitable for conventional incineration and co-incineration due to the required pre-processing and increased operating temperatures. Moreover, landfilling is a problematic option since carbon fibers are chemically inert and degrade slowly [23].

In general, a suitable recycling method for carbon fibers should be efficient, environmentally friendly, have minimal impact on fiber length and allow interfacial compatibility with new resins [24]. Moreover, an environmentally sound recycling method should cause less overall environmental impact than the production process of primary raw material or other waste management methods [23]. In this regard, there are mainly three recycling methods for carbon fibers: mechanical recycling, thermal recycling and chemical recycling [20,24].

Thermal recycling includes pyrolysis as well as fluidized bed pyrolysis, while chemical recycling includes solvolysis (with near- or supercritical fluid) and acid digestion [25]. Among these methods, pyrolysis and mechanical recycling show a better technological readiness [21] compared to chemical recycling or fluidized bed pyrolysis [20,25]. For mechanical recycling, this is due to the energy efficiency in high production rates and production capacities, as well as the lower costs [25,26]. In the case of pyrolysis, this is currently the most technologically advanced method for the recycling of carbon fibers and has already proven its economic feasibility in large-scale plants [27]. For these reasons, only mechanical recycling and pyrolysis will be discussed below.

2.1.1. Mechanical Recycling

One advantage of mechanical recycling (Figure 1) is that it can address the growing amounts of carbon fiber waste [25]. This is because, in this method, the fiber composite material is shredded and milled through a multi-stage process [28]). For this purpose, equipment such as multi-shaft shredders and granulators are used, followed by the screening of the fibers to obtain a homogeneous particle size distribution [29,30]. In mechanical recycling, the fibers cannot be completely separated from the matrix (impregnation as EP or SBR) [28,31]. However, recycling can also take place without the separation of these two components [32]. The shredded carbon fibers can be used as fillers in composites, concrete, asphalt and coatings, which would involve downcycling the fibers [29,32–34]. The use of fillers consisting of recycled carbon fibers can increase mechanical (e.g., fatigue and fracture) as well as tribological properties (e.g., friction and wear) of new pure plastics [29,35]. In summary, the rapid processing and ease of scalability are major advantages of this recycling method, but the length of the carbon fibers is greatly reduced and contains resin residues, which in turn affects their recyclability in new products [25]. Technically, the term 'mechanical recycling' would also comprise the technologies of electrodynamic and electrohydraulic fragmentation, which separate resin and carbon fiber (CF) under high voltage. However, as they are still at lab-scale, they are excluded from this study [36].

2.1.2. Pyrolysis

Pyrolysis is a recycling method that can produce recycled carbon fibers on a large scale (Figure 1), with an estimated total energy consumption of 5–10% of the total energy required to produce primary fibers [23,25]. Compared to mechanical recycling, a fundamental advantage of pyrolysis is that the polymer matrix (impregnation) can be completely parted from the carbon fibers, thus enabling split recycling of the fibers and polymer matrix [29,32]. These are separated in an inert atmosphere (usually nitrogen) under atmospheric pressure at a controlled temperature of at least 350 °C [24,37,38]. During this process, so-called pyrolysis gases (e.g., H_2, CH_4, CO and CO_2) are emitted from the polymer matrix [39,40]. Due to their high calorific value, these can be reused as fuel to directly support pyrolysis and offset some of the electricity (or natural gas), necessary as inputs for the pyrolysis [12,20,41,42]. Burning off the polymer matrix can cause soot adhesion to the carbon fiber surface, which would prevent the fibers from bonding well with new resin [24,27]. For this reason, subsequent oxidation is necessary, which can remove the carbon black particles but harms the mechanical properties of the carbon fibers (elastic modulus and tensile strength) [40,42–45]. The extent of this damage depends largely on the operating conditions such as pyrolysis and oxidation temperatures, residence time and reaction atmosphere [25]. In this regard, the best mechanical properties (93% of tensile strength and 96% of the elastic modulus) have been obtained at a pyrolysis and oxidation temperature of 500 °C, a pyrolysis time of one hour and an oxidation time of two hours [46]. The oxidation process may additionally enrich the pyrolyzed fibers with oxidized groups, thus serving as a crosslinker between the recycled fibers and new resin [47].

However, it has been reported that the composites made with recycled carbon fibers tend to have lower mechanical properties compared to the composites made with primary fibers [25]. They can be used to increase the strength of plastics in injection molded components as well as further processed into nonwovens [12]. Therefore, the recycled fibers find application only in the field of non-structural composites such as cladding in the automotive and aerospace industries or lightweight sports equipment [12,43,47]. We exclude in our study the technology of microwave-assisted pyrolysis. Although it has lower energy needs, it is still at the laboratory stage, and the quality of the recovered CF is lower compared to conventional pyrolysis [22]. We also exclude fluidized bed pyrolysis for CF recovery due to its lab stage status too.

2.2. State-Of-The-Art: End-Of-Life Life Cycle Assessment Implementations to CRC

In many scientific articles on environmental assessments of CRC, most notably Stoiber et al. (2021) [48], Laiblová et al. (2019) [49] and Williams Portal et al. (2015) [50], recycling is generally not considered. However, the authors of these works call for an environmental assessment of the EoL, pointing out, on the one hand, the good recyclability of the reinforcement material steel that is already in practice and, on the other hand, the difficult recycling procedures for CRC, which is the aim of the current research [51,52]. An environmental assessment of the recycling of CRC has so far only been performed by Scope et al. (2020) [53] and Hatzfeld et al. (2022) [54]. Scope et al. (2020) [53] conducted a cradle-to-grave Life Cycle Sustainability Assessment (LCSA) on a CRC double wall, encompassing the environmental, economic and social dimension. However, for the EoL, they found that recycling can hardly provide an environmental benefit according to the CML environmental impact categories results. The authors modeled a pyrolysis recycling of the CFRP fraction according to Meng et al. (2018) [55] and crediting for recycled carbon fibers use as a substitute for primary glass fiber in a glass fleece. Nevertheless, this study omits deconstruction and separation processes as well as the mechanical recycling. Inspired by these findings, Hatzfeld et al. (2022) [54] map multiple recycling paths of CRC and its components. For the individual processes, they provide a measure of technological maturity using Manufacturing Readiness Levels (MRL) and state the literature-based GWP values, giving recommendations for a technologically feasible and environmentally sound recycling of CRC [54].

2.2.1. Life Cycle Assessment of Mechanical Recycling and Pyrolysis

There are numerous environmental assessments on mechanical recycling and pyrolysis of CFRP in the scientific literature. Namely, for pyrolysis, the studies by Gopalraj et al. (2021) [18], He et al. (2020) [56], Khalil et al. (2018) [20], Vo Dong et al. (2018) [57], Dieterle et al. (2017) [58], Meng et al. (2018) [55], Pillain et al. (2019) [36] and Nunes et al. (2018) [59] can be highlighted. Studies focusing on the mechanical recycling of carbon fibers are Li et al. (2016) [60], Meng et al. (2018) [55], Shuaib and Mativenga (2017) [61] and Howarth et al. (2014) [26]. All mechanical recycling and pyrolysis studies have consistent findings for the respective technologies. First of all, they show that recycled carbon fiber (rCF) has a better environmental performance than virgin carbon fiber (vCF). The mechanical recycling process is generally found to have the lowest environmental impacts. However, as pyrolysis can recover higher quality recycled CF components by maintaining more of the structural integrity and length of the fibers, it allows for more options to substitute vCF. Hence, if crediting is applied, the pyrolysis achieves better results. If the rCF is used as a substitute for other products, such as glass and steel fibers, environmental performance worsens [53,62].

2.2.2. Life Cycle Assessment of Recycling of Concrete Fragments

Environmental assessment studies on the recycling of concrete in the scientific literature vary heavily in their results, depending on assumptions regarding transport distances, concrete specifications, stationary or mobile recycling, type of recycling processes, country, data sources for the Life Cycle Inventory and application of the recyclate. Current common uses for recycling concrete aggregate (RCA) are backfills, road sub-base and base, i.e., downcycling. These recycling routes are modelled in environmental assessments by Guignot et al. (2015) [63], Martinez-Arguelles et al. (2019) [64] and Wei et al. (2013) [65]. Although the use of RCA does not significantly lower GWP, it prevents the depletion of natural aggregates, which are becoming increasingly scarce.

RCA application is as an alternative to natural aggregates in structural concrete, a higher quality application in comparison to its implementation in road construction. There are many environmental assessments on this recycling route, collected in two LCA studies and reviews by Colangelo et al. (2020) [66], Mostert et al. (2021) [67], Yazdanbakhsh et al. (2018) [68], Guo et al. (2018) [69], Fraj and Idir (2017) [70], Kleijer et al. (2017) [71], Braga et al. (2017) [72], Müller et al. (2015) [73], Serres et al. (2016) [74], Turk et al. (2015) [75], Mettke et al. (2015) [76], Knoeri et al. (2013) [77], Weimann et al. (2013) [78], Heyn and Mettke (2010) [79], Marinković et al. (2010) [80] and Bischof et al. (2010) [81]. In most studies, the results show that the GWP is not significantly lower, as the crushing of the concrete and the transport have high energy needs, and there is still the need to add primary cement to the concrete mix. However, results vary greatly. The GWP of RCA concrete ranges from 20% less to 35% more than natural aggregate concrete. This large variation is due to the different assumptions made in the studies. Furthermore, there is a method that allows a closed-loop recycling of concrete—electrodynamic fragmentation. This method allows for separate reclaiming of the cement fragments and the aggregate fragments. Respective environmental assessments are conducted by Gehring et al. (2015) [82] and Guignot et al. (2015) [63]. However, this technology is still in the laboratory stage, and due to the high energy needs of this method, the environmental impacts are not significantly lower.

3. Methodology

3.1. Goal and Scope

This study aims to present the range of environmental impacts of CRC after its use phase until re-usable material fractions are obtained using LCA. Accordingly, the scope of the study is defined from demolition to waste management (= C1–C3 in DIN EN 15804) [83]. The following scenarios are based on ISO 14040/44 and are modeled with GaBi ts 10.5.1.124 [84,85]. In addition, production in Germany is assumed, which is why any energy supply was modeled with German input processes. The impact categories used are in line with the CML2001 (August 2016) methodology [86]. The Functional Unit (FU) is mass in kg of re-usable material, originating from the CRC double-wall described by Otto and Adam (2019) [87], with dimensions (per wall) of 5 × 2.5 × 0.25 m and a total weight of 1.43 t (of which concrete 1.42 t and 0.0102 t scrim per double-wall) or 0.6 m^3 [87,88]. The reason for kg as a FU is to understand what percentage of the original wall can ultimately be reused and not end up as waste. External joining elements to the double wall, as well as optional insulation materials are not included in the LCA.

3.2. Life Cycle Inventory

This life cycle inventory (Table 1) is based on the process sequence explained in Section 2 (Figure 1). The energy values and the transports including fuel refer exclusively to the functional unit (1 kg of re-usable material) and accordingly not to the complete double-wall. In this context, reference flow for our study is 0.993 kg of concrete and 0.007 kg of carbon reinforcement. The entire life cycle inventory is based on literature data or datasheets from German companies, which were converted to the target value according to justified assumptions. A detailed description of the individual assumptions and calculations made can be found in the Supplementary Material (A.1).

Table 1. Inventory Demolition.

Process	Mass Unit	Input	GaBi Process	Assumption/Reference
Selective demolition with pre-crushing	MJ/kg	0.03382	Modeled process DE: Diesel mix at filling station Sphera	Machinery and related net power: [89,90] Fuel consumption: [91]
Transport of the material to the stationary processing plant	km	17	GLO: Truck, Euro 4, 26–28t gross weight/18.4t payload capacity	[92]
Loading of the demolition material with excavator (in the processing plant)	MJ/kg	0.0047	Modeled process DE: Diesel mix at filling station Sphera	[89]

Table 1. *Cont.*

Process	Mass Unit	Input	GaBi Process	Assumption/Reference
Main crushing with concrete crusher (jaw crusher or impact mill)	MJ/kg	0.035	Modeled process DE: Diesel mix at filling station Sphera	[89]
Pre-separation with stationary magnetic separator in combination with cross flow sifter	MJ/kg	0.0072	Modeled process DE: Electricity grid mix (2020) ts	[89]
Main separation (camera-based sorting)	MJ/kg	0.0054	Modeled process DE: Electricity grid mix (2020) ts	[93]
Sieving	MJ/kg	0.0000385	Modeled process DE: Diesel mix at filling station Sphera	[89]
Discharge to the bunker with wheel loader	MJ/kg	0.0057	Modeled process DE: Diesel mix at filling station Sphera	[89]
Transport from the processing plant to further recycling	km	100	GLO: Truck, Euro 4, 12–14t gross weight/9.3t payload capacity	Authors' assumption

3.2.1. Recycling Option 1: Mechanical Recycling

Mechanical recycling (Table 2) consumes 0.27 MJ per kg of carbon fiber reinforced composite waste [26,94].

Table 2. Inventory mechanical recycling.

Process	Mass Unit	Input	GaBi Process	Assumption/Reference
Mechanical recycling	MJ/kg	0.00189	Individually modelled process DE: Electricity grid mix (2020) ts	[26,94]

To determine the energy value, Howarth et al. (2014) [26] used the energy equation developed after Gutowski et al. (2006) [95]: $E = (P_0 + kQ)t$ [26,95]. Here, P_0 describes the basic power, k the specific energy for comminution of a given material, Q the rate of study and t the total study time. To determine these parameters, 1 kg of carbon-fiber-reinforced composite sheets with a thickness of 3 mm were fed to an industrial shredding machine. A basic power of 5248 W, specific energy of 0.218 J/mm^3 and a required loading time of 6 min was measured for the comminution of 1 kg of carbon-fiber-reinforced composite sheets, and a consequent rate of 10 kg per hour was calculated. Subsequently, these parameters were used in the energy equation and resulted in process energy of 2.03 MJ/kg. It should be noted that, according to the machine manufacturer, steady rates of up to 150 kg per hour are possible. [26] If this rate is used, the energy equation developed by Gutowski et al. (2006) [95] yields process energy of 0.27 MJ/kg [26,95]. Consequently, mechanical recycling at high rates or industrial scale is more energy efficient [26], thus reducing emissions per kg processed material.

The energy consumption of 0.27 MJ per kg of carbon fiber reinforced composite waste reported by Hedlund-Åström (2005) [94] was provided by the Swedish recycling company Jomill AB [94]. This energy consumption was offset against the mass of carbon reinforcement (0.007 kg), resulting in 1.89×10^{-3} MJ. This consumption was modeled in GaBi using the input process "DE: Electricity grid mix (2020) ts".

3.2.2. Recycling Option 2: Pyrolysis

Pyrolysis (Table 3) consumes 7.6 MJ (from electricity) and 13.2 MJ (from natural gas) per kg of carbon fiber reinforced composite waste [55].

These energy-related inventory data were used from a commercial operation of ELG Carbon Fibre Ltd., according to Meng et al. (2018) [55]. The two energy values were each offset by the mass of carbon reinforcement (0.007 kg), resulting in 0.0532 MJ (electricity) and 0.0924 MJ (natural gas). The energy consumption by the electricity was modeled with the input process "DE: Electricity grid mix (2020) ts" and the energy consumption by the natural gas with the input process "DE: Natural gas mix Sphera".

Table 3. Inventory pyrolysis.

Process	Mass Unit	Input	GaBi Process	Assumption /Reference
Pyrolysis	MJ/kg	 0.0532 0.0924	Individually modelled process DE: Electricity grid mix (2020) ts DE: Natural gas mix Sphera	[55]

4. Life Cycle Impact Assessment Results: Focusing on the Carbon Footprint

In this study, we use the impact categories according to the CML2001 (August 2016) methodology [86]. In this section, we refer primarily to the impact category Global Warming Potential (GWP in kg CO_2e). In the first section (recycling phase 1), the selective demolition up to the transport of the carbon fibers for further recycling is presented as recycling phase 1. Further recycling (mechanical recycling and pyrolysis) is defined as recycling phase 2. A division of the impact assessment into two sections was made, because the recycling process of the carbon concrete up to this limit is independent of the further recycling of the carbon fibers. Future life cycle assessments, which investigate further recycling processes for the carbon fibers contained in the carbon concrete (e.g., solvolysis), are thus offered the possibility of applying the emission values determined in recycling phase 1 for the separation of the concrete from the carbon fibers. Finally, we assume the recycled concrete partly being used for road construction.

4.1. Recycling Phase 1

Figure 2 shows the GWP in kg CO_2e of the recycling process before further recycling (mechanical recycling and pyrolysis), per process. Among all the processes (listed in Table 1), transportation to a stationary processing plant shows the highest GWP value, while screening shows the lowest. The sum of global warming potentials for all processes totals 4.2×10^{-3} kg CO_2e. Among the two processes operated with "DE: Electricity grid mix (2020) ts" (pre-separation and main separation), the pre-separation has the highest GWP with 1.2×10^{-3} kg CO_2e. For the processes operated with "DE: Diesel mix at filling station Sphera", the main crushing shows the highest GWP with 2.7×10^{-4} kg CO_2e and screening shows the lowest GWP with 3.0×10^{-7} kg CO_2e. Furthermore, transportation to further recycling shows a lower GWP with 8.4×10^{-5} kg CO_2e.

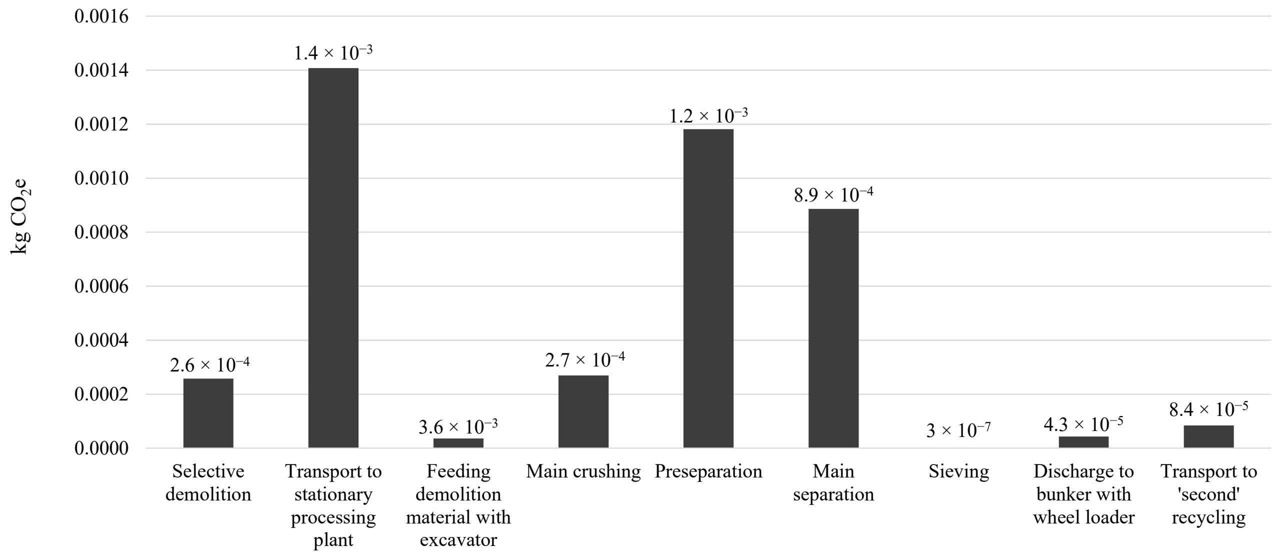

Figure 2. Global warming potential in kg CO_2e of 1 kg re-usable material out of a double wall—recycling phase 1.

4.2. Recycling Phase 2 ('Second' Recycling)

Recycling phase 1 is followed by an impact assessment for further recycling of the carbon fibers contained in the CRC. Figure 3 shows both the GWP of mechanical recycling and the GWP of pyrolysis. Pyrolysis has a higher GWP of 9.7×10^{-3} kg CO_2e than mechanical recycling with 3.1×10^{-4} kg CO_2e.

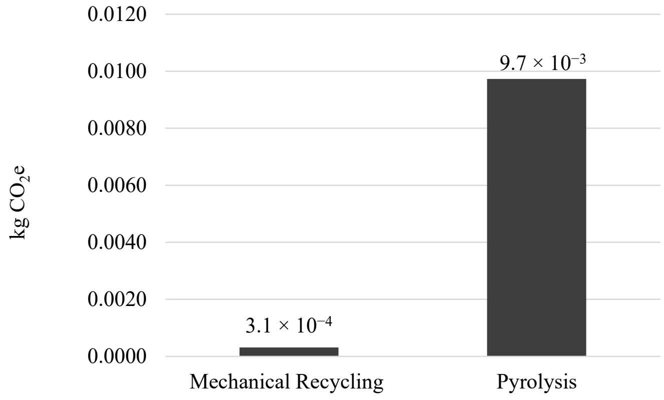

Figure 3. Global warming potential in kg CO_2e of 1 kg re-usable material out of a double wall—recycling phase 2.

Adding the respective GWP of the two recycling processes (mechanical recycling and pyrolysis) to the GWP of 4.2×10^{-3} kg CO_2e calculated in recycling phase 1, we finally obtain a total GWP of 4.5×10^{-3} kg CO_2e from mechanical recycling and 1.4×10^{-2} kg CO_2e from recycling within pyrolysis.

4.3. Use of Recycled Carbon Fiber Fragments

A long residence time of the carbon fibers in the material cycle is the aim since the carbon fibers represent a valuable and energy-intensive material [12]. Mechanical recycling and pyrolysis do not yet include a variant in which the carbon fibers are added back to the material cycle and, for example, a new carbon reinforcement is produced from the recycled carbon fibers. One theoretical solution is to process the recycled carbon fibers into staple fiber yarns [12]. In a carding process, the staple fiber yarns can be processed as hybrid yarns from a proportion of reprocessed carbon fibers and thermoplastic fibers (e.g., polyamide) and then carded, bundled and deposited on bobbins [12]. Hybrid yarns developed at the TU Dresden showed a bond strength of 1100 N/mm^2, which corresponds to a comparative value of 48% and 55% of the 'primary raw material' strength of the carbon reinforcement of 2300 N/mm^2 and 2000 N/mm^2 used in CRC at the beginning [12,96]. Considering that, according to Yang et al. (2015) [45], up to 80% of the tensile strength potential of pyrolyzed fibers is achieved compared to primary fibers, the recycled carbon fibers resulting from pyrolysis could be processed into yarn structures and reprocessed into textile structures (e.g., rods or scrims) as reinforcement in concrete components [12,45].

It should be noted that we do not have exact energy values for the processing procedure nor a quantitative ratio of recycled carbon fibers in the hybrid yarns given. For this reason, no further crediting for recycled carbon fibers is performed.

4.4. Reuse of Concrete Fragments

Compared to the recycling of carbon fibers, a view across the system boundary in terms of the processed concrete fraction is both theoretically and practically feasible. Dwindling resource sources for the extraction of suitable sands and gravels, as well as the rising cost of landfilling waste, have contributed to the fact that the recycling of mineral building materials has long been the focus of practical construction and scientific activities [97]. Moreover, the mineral concrete fraction can be almost completely recycled through singlevariety processing, as well as theoretically reused several times in an ideal recyclable material cycle [31].

It is possible to use the concrete fraction recycled in the stationary processing plant for the production of concrete made of primary raw material. According to Kortmann (2020) [12], the mineral fraction is in the coarse-grained and wide-graded aggregate 3/56 after completion of recycling. For the production of concrete, the mineral fraction should be crushed and classified to the narrow-graded aggregate 2/8 or 8/16. The maximum permissible volume fraction of the recycled concrete fraction that may be added during the production of concrete made of primary raw material is defined in DIN EN 12620 (07/2008) by classification into delivery type 1 or 2 [98]. The two delivery types are defined by DIN 4226-101 (08/2017) [99]. [12] A classification of the recycled concrete fraction into the two delivery types is based on the material composition. According to DIN EN 12620 (07/2008) [98], a volume fraction of up to 45% can be added to delivery type 1 and a volume fraction of up to 35% can be added to delivery type 2 in the production of concrete made of primary raw material [100].

Despite an existing mass fraction of the reinforcement structures of 0.023% within the recycled concrete fraction, the concrete fraction can be assigned to delivery type 1, since the plastic mass fraction is less than 1%. Consequently, no additional separation of the remaining reinforcement structures in the recycled concrete fraction is necessary, and it can be crushed and classified directly for further use as a substitute material for the production of concrete made of primary raw material to a narrow-graded grain size of 2/8 or 8/16 [12].

To investigate a potential emission saving by using the recycled aggregate from the concrete demolition, a comparison to primary raw material concrete is made. For this purpose, it was assumed that the resulting recycled concrete fraction, as described by Kortmann (2020) [12], corresponds to the grain size 3/56 and is first crushed to a narrow-graded grain size 8/16 and 2/8 [12]. Furthermore, it was assumed that the recycled aggregate is transported to another stationary processing plant where it is crushed. In this respect, we follow the process sequence, as well as the results of the research project of the University (BTU) Cottbus, worked on by Mettke and Heyn (2010) [79], which examined the process sequence for the production of the recycled aggregate in a stationary processing plant of the company Scherer + Kohl GmbH and Co. KG concerning the energy consumption [79]. The evaluation in GaBi showed that the preparation of 0.993 kg of concrete fraction has a total GWP of 6.9×10^{-3} kg CO_2e.

To compare the production of concrete without the use of the recycled concrete fraction with the production of concrete with the use of recycled material, a concrete formulation must first be defined. For this purpose, the commonly used concrete C30/37 from the company TBS was used [79] (Figure 4).

Concerning the production of one m^3 of common used concrete C30/37, the GWP that arises for the 2/8 and 8/16 gravel is determined below. For this purpose, the input process "DE: Gravel (Grain size 3/32)" was used, according to which the production of 1 kg of gravel has a GWP of 2.8×10^{-2} kg CO_2e. It should be noted that in GaBi no exact differentiation of grain sizes was possible, so it is simplified to assume that the production of 1 kg of gravel shows the same GWP for both grain sizes 2/8 and 8/16. For the production of one m^3 of common used concrete C30/37 according to TBS, 363 kg of 2/8 gravel and 729 kg of 8/16 gravel are required [79]. Offsetting the mass of gravel required per m^3 of common used concrete C30/37 with the GWP of 1 kg of gravel results in a gravel-derived GWP of 30.6 kg CO_2e per m^3 of common used concrete C30/37.

The recycled concrete fraction is assigned to delivery type 1 and can accordingly be added to the production of concrete made of primary raw material up to a volume fraction of 45%. According to the data of Mettke and Heyn (2010) [79], 34.5% of the concrete demolition waste is converted into 8/16 grain size and 13.8% into 2/8 grain size. Consequently, from the 0.993 kg of recycled concrete fraction, a total of 0.343 kg is processed into 8/16 grain size and 0.137 kg into 2/8 grain size. Since for the production of one m^3 of common used concrete C30/37 (without the use of the recycled concrete fraction) no differentiation was possible for the GWP of the different grain sizes of the gravel (2/8 and 8/16), it is also assumed here that both grain sizes have the same GWP. Previously, the GWP for the processing of 0.993 kg of concrete fraction or the resulting recycled 0.137 kg of the 2/8 and 0.343 kg of the 8/16 aggregate was determined to be 6.9×10^{-3} kg CO_2e. Assuming that the GWP is not differentiated for the aggregate sizes, the GWP is 0.014 kg CO_2e per kg of recycled aggregate. If the total gravel required to produce one m^3 of standard C30/37 concrete (363 kg of 2/8 gravel + 729 kg of 8/16 gravel = 1092 kg of gravel in total) is composed of 45% recycled aggregate, the GWP is 23.7 kg CO_2e.

Thus, with the use of the recycled aggregate in the production of one m^3 of common used concrete C30/37, a total of 6.9 kg CO_2e per m^3 of common used concrete C30/37 is saved compared to the production without the use of the recycled aggregate (substitution of gravel), which corresponds to a percentage reduction of 22.5%.

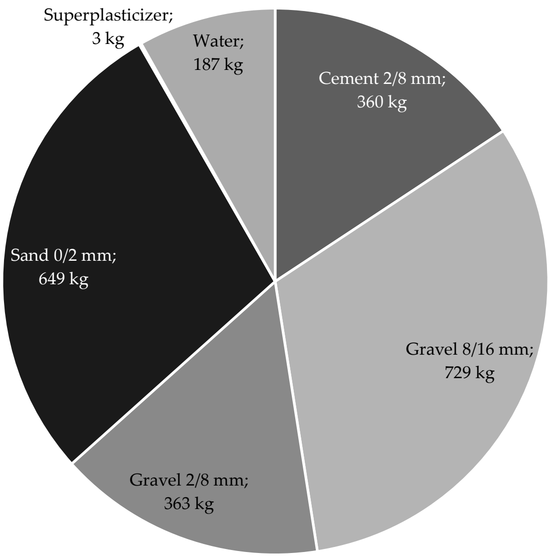

Figure 4. Concrete materials in kg (according to [79]).

5. Discussion and Limitations

In this study, we consider the EoL of CRC. The sustainability assessment of CRC of the EoL is highly relevant, as it enables the environmental impact of the recycling process to be determined at an early stage and can thus address the question of whether CRC has the potential to play a decisive role in improving the built environment given the current climate crisis. This question must be answered as early as possible, since the intended commercialization of CRC, mainly motivated by concrete or cement savings, is accompanied by a large investment in research and development as well as the establishment of new construction guidelines. For these reasons, the LCA of the EoL of CRC must in the future be connected to an analysis of the environmental impacts of the production and use stages to map the complete life cycle of the material. This connection would allow a comprehensive comparison of the environmental performance of CRC with conventional variants, such as steel-reinforced concrete.

Within the system boundaries, the selective demolition and the transport of the carbon fibers for further recycling were defined as recycling phase 1, while the further recycling (mechanical recycling and pyrolysis) as recycling phase 2. For recycling phase 1, transport to the stationary processing plant showed the highest GWP with 1.4×10^{-3} kg CO_2e, and screening showed the lowest GWP with 3.0×10^{-7} kg CO_2e. Transport to the stationary processing plant, as the main driver of GWP, highlights the need for processing plants at a short distance that have the technical implementation capabilities to recycle CRC. It stands out that among the processes taking place in the stationary processing plant, the only two processes powered by electricity, the pre-separation with 1.2×10^{-3} kg CO_2e and the main separation with 8.9×10^{-4} kg CO_2e, also show the largest GWP. The use of renewable energy sources could lead to further emission savings.

For the subsequent recycling phase 2, pyrolysis showed a higher GWP with 9.7×10^{-3} kg CO_2e than mechanical recycling with 3.1×10^{-4} kg CO_2e. It should be emphasized that although mechanical recycling shows a lower GWP, the inferior quality of the recycled carbon fibers and the resulting lower range of recycling options for new products represent significant disadvantages compared to pyrolysis. The importance of the closed material cycle and the associated preparation of the recycled carbon fibers into a new carbon reinforcement is emphasized in this work. This stems from both the high energy input and the dependence on the non-renewable raw material petroleum for the production of primary carbon fibers. In this respect, mechanical recycling represents the overall process with the lowest energy input but does not have the decisive potential to close the material cycle compared to pyrolysis.

In this work, it was also assumed that the concrete fraction separated from the CRC and subsequently recycled can be successfully used as a substitute material for the production of concrete made of primary raw material. It was determined that with the use of the recycled material in the production of one m^3 of common used concrete C30/37, 22.5% of primary raw material concrete GWP could be saved. These results illustrate two important points: first, the emission savings through the use of recycled aggregate and second, the possibility of partially closing the material cycle of the concrete fraction.

The central limitation of our study arises from the fact that CRC is a new type of composite construction material, and no primary data is currently available for the energy consumption of recycling. Consequently, the consumption data used in the life cycle inventory are secondary data not explicitly related to CRC. Therefore, the implemented data only provide reference values for a possible recycling process. The life cycle inventory is also limited by the fact that:

- The consumption data of the selective demolition according to Klingler et al. (2021) [89] refer to weakly reinforced concrete and not CRC [89];
- The calculation of transport distances only represents a theoretical approximation [12,92];
- Energy consumption represents the average electricity consumption of German companies, determined from previous literature [89,93], not measured values;
- Operating conditions such as pyrolysis and oxidation temperatures, residence time and reaction atmosphere of the ELG Carbon Fibre Ltd. pyrolysis plant were not reported by Meng et al. (2018) [55] (only the total energy consumption), and energy consumption may differ significantly compared to other pyrolysis plants [55];
- A variance in energy consumption results from the different machines is possible for mechanical recycling.

These limitations should be optimized in subsequent studies by using primary data from recyclers that explicitly recycled CRC. This requires both details on pyrolysis and any energy consumption. In addition, the consideration of the entire life cycle is relevant, and also the direct comparison with a functionally comparable reinforced concrete component will provide further insights regarding the environmental performance of CRC.

6. Conclusions

This study aimed to assess the environmental performance of the recycling of CRC considering the scenarios of mechanical recycling and pyrolysis and to determine the associated energy consumption to enable an environmental assessment (focusing GWP) of CRC at the end of its life cycle.

To date, articles on CRC have not fully considered recycling in terms of its environmental impact. Very few studies have looked at the EoL of CRC. The novelty of this article is the detailed presentation of possible EoL scenarios for CRC and the detailed determination of the respective environmental scenarios for a double wall of CRC. Especially for practitioners in the construction sector, the relevance of this article is that the entire life cycle of new material such as CRC should be considered, especially during the design phase. Moreover, the EoL can have relevant impacts on the environmental emissions, and due to an increasing interest in sustainability in the construction sector, our LCA scenarios clarified first approaches for the future of this sector. The determined energy consumption for the elaborated recycling process meets the lack of primary data of CRC recycling and enables future life cycle assessments, which, e.g., investigate further recycling methods for the carbon fibers contained in the CRC to apply the used energy input data, which accrue for the separation of the concrete fraction from the carbon fiber fraction.

The LCA with the system boundary demolition to recyclable material, with the functional unit of 1 kg of recyclable material from a double-wall according to Otto and Adam (2019) [88] was modeled using literature-based data in GaBi ts software and CML2001 (2016) methodology. The main drivers of the GWP represent transport and pyrolysis. For the demolition and separation of both the concrete and the carbon fiber fractions, the conventional transport from the demolition site to the stationary processing plant proved to be the main driver of GWP (1.4×10^{-3} kg CO_2e). In the subsequent processing of carbon fibers, pyrolysis showed a higher GWP (9.7×10^{-3} kg CO_2e) than mechanical recycling (3.1×10^{-4} kg CO_2e). It should be emphasized that although mechanical recycling shows a lower GWP, the inferior quality of the recycled carbon fibers and the resulting lower range of recycling options for new products represent significant disadvantages compared to pyrolysis.

The concrete fraction separated from the CRC and subsequently recycled can be successfully used as a substitute material for the production of concrete made of primary raw material. The use of the recycled material in the production of one m^3 of commonly used concrete C30/37 corresponds to a percentage reduction of 22.5% (saving of 6.9 kg CO_2e).

Finally, further studies should consider the entire life cycle of CRC (including construction, life time and EoL) and ensure a direct comparison with a functionally equivalent component made of steel-reinforced concrete.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr10091791/s1, Supplementary Material (A.1).

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Conflicts of Interest: The authors declare no conflict to interest.

Abbreviations

CF	carbon fiber(s)
CFRP	carbon fiber reinforced plastics
CRC	carbon reinforced concrete
DIN	Deutsches Institut für Normung
EoL	End-of-Life
EP	epoxy resin
FU	Functional Unit
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
MRL	Manufacturing Readiness Levels
PAN	polyacrylonitrile

RCA	recycling concrete aggregate
rCF	recycled carbon fiber
SBR	styrene-butadiene rubber
vCF	virgin carbon fiber

References

1. Choi, J.-H. Strategy for reducing carbon dioxide emissions from maintenance and rehabilitation of highway pavement. *J. Clean. Prod.* **2018**, *209*, 88–100. [CrossRef]
2. Ding, T.; Xiao, J.; Tam, V.W.Y. A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. *Waste Manag.* **2016**, *56*, 367–375. [CrossRef] [PubMed]
3. Sameer, H.; Bringezu, S. Life cycle input indicators of material resource use for enhancing sustainability assessment schemes of buildings. *J. Build. Eng.* **2018**, *21*, 230–242. [CrossRef]
4. Elbers, U. Ressourcenschonendes Bauen—Wege und Strategien der Tragwerksplanung. *Bautechnik* **2021**, *99*, 57–64. [CrossRef]
5. Blandini, L. Ressourceneffizientes und klimagerechtes Bauen mit Beton–eine Illusion? *Beton Stahlbetonbau* **2021**, *116*, 717. [CrossRef]
6. Chung, S.-Y.; Abd Elrahman, M.; Stephan, D.; Kamm, P.H. The influence of different concrete additions on the properties of lightweight concrete evaluated using experimental and numerical approaches. *Constr. Build. Mater.* **2018**, *189*, 314–322. [CrossRef]
7. Ramana, P.V.; Agnihotri, A. Fly-ash conjoined ground granulated blast furnace slag proxy for fresh and hardened responses. *Mater. Today Proc.* **2021**, *49*, 1942–1949. [CrossRef]
8. Seifert, W.; Lieboldt, M. Ressourcenverbrauch im globalen Stahlbetonbau und Potenziale der Carbonbetonbauweise. *Beton- und Stahlbetonbau* **2020**, *115*, 469–478. [CrossRef]
9. Guerra, B.C.; Leite, F. Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. *Resour. Conserv. Recycl.* **2021**, *170*, 105617. [CrossRef]
10. Kraft, R.; Kahnt, A.; Grauer, O.; Thieme, M.; Wolz, D.S.; Schlüter, D.; Tietze, M.; Curbach, M.; Holschemacher, K.; Jäger, H.; et al. Advanced carbon reinforced concrete technologies for façade elements of nearly zero-energy buildings. *Materials* **2022**, *15*, 1619. [CrossRef]
11. OECD. *Global Material Resources Outlook to 2060. Economic Drivers and Environmental Consequences*; OECD Publishing: Paris, France, 2019.
12. Kortmann, J. *Verfahrenstechnische Untersuchungen zur Recyclingfähigkeit von Carbonbeton*; Springer: Berlin/Heidelberg, Germany, 2020. [CrossRef]
13. Monteiro, P.J.M.; Miller, S.; Horvath, A. Towards sustainable concrete. *Nat. Mater.* **2017**, *16*, 698–699. [CrossRef] [PubMed]
14. Reichenbach, S.; Preinstorfer, P.; Hammerl, M.; Kromoser, B. A review on embedded fibre-reinforced polymer reinforcement in structural concrete in Europe. *Constr. Build. Mater.* **2021**, *307*, 124946. [CrossRef]
15. Spelter, A.; Bergmann, S.; Bielak, J.; Hegger, J. Long-Term Durability of Carbon-Reinforced Concrete: An Overview and Experimental Investigations. *Appl. Sci.* **2019**, *9*, 1651. [CrossRef]
16. Goulouti, K.; Favre, D.; Giorgi, M.; Padey, P.; Galimshina, A.; Habert, G.; Lasvaux, S. Dataset of service life data for 100 building elements and technical systems including their descriptive statistics and fitting to lognormal distribution. *Data Brief* **2021**, *36*, 107062. [CrossRef]
17. Grant, A.; Ries, R. Impact of building service life models on life cycle assessment. *Build. Res. Inf.* **2012**, *41*, 168–186. [CrossRef]
18. Gopalraj, S.K.; Deviatkin, I.; Horttanainen, M.; Kärki, T. Life cycle assessment of a thermal recycling process as an alternative to existing CFRP and GFRP composite wastes management options. *Polymers* **2021**, *13*, 4430. [CrossRef]
19. Stockschläder, J.; Quicker, P.; Baumann, W.; Wexler, M.; Stapf, D.; Beckmann, M.; Thiel, C.; Hoppe, H. Thermal treatment of carbon-fibre-reinforced polymers (Part 2: Energy recovery and feedstock recycling). *Waste Manag. Res. J. Sustain. Circ. Econ.* **2021**, *40*, 685–697. [CrossRef]
20. Khalil, Y. Comparative environmental and human health evaluations of thermolysis and solvolysis recycling technologies of carbon fiber reinforced polymer waste. *Waste Manag.* **2018**, *76*, 767–778. [CrossRef]
21. Rybicka, J.; Tiwari, A.; Leeke, G.A. Technology readiness level assessment of composites recycling technologies. *J. Clean. Prod.* **2016**, *112*, 1001–1012. [CrossRef]
22. Shuaib, N.A.; Mativenga, P. Carbon footprint analysis of fibre reinforced composite recycling processes. *Procedia Manuf.* **2017**, *7*, 183–190. [CrossRef]
23. Witik, R.A.; Teuscher, R.; Michaud, V.; Ludwig, C.; Månson, J.-A.E. Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. *Compos. Part A Appl. Sci. Manuf.* **2013**, *49*, 89–99. [CrossRef]
24. Oliveux, G.; Dandy, L.O.; Leeke, G.A. Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. *Prog. Mater. Sci.* **2015**, *72*, 61–99. [CrossRef]
25. Pakdel, E.; Kashi, S.; Varley, R.; Wang, X. Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes. *Resour. Conserv. Recycl.* **2020**, *166*, 105340. [CrossRef]
26. Howarth, J.; Mareddy, S.S.; Mativenga, P.T. Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite. *J. Clean. Prod.* **2014**, *81*, 46–50. [CrossRef]

27. Limburg, M.; Quicker, P. Entsorgung von carbonfasern—Probleme des recyclings und auswirkungen auf die abfallverbrennung. *Berl. Abfallwirtsch. Energ.* **2016**, *13*, 135–144.
28. Woidasky, J.; Seiler, E.; Henning, F.; Wolf, M.-A.; Harsch, M. Kunststoffe und bauteile–Umwelt und recycling. In *Polymer Engineering 3*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 89–139. [CrossRef]
29. May, D.; Goergen, C.; Friedrich, K. Multifunctionality of polymer composites based on recycled carbon fibers: A review. *Adv. Ind. Eng. Polym. Res.* **2021**, *4*, 70–81. [CrossRef]
30. Vincent, G.A.; de Bruijn, T.A.; Wijskamp, S.; Rasheed, M.I.A.; van Drongelen, M.; Akkerman, R. Shredding and sieving thermoplastic composite scrap: Method development and analyses of the fibre length distributions. *Compos. Part B Eng.* **2019**, *176*, 107197. [CrossRef]
31. Martens, H.; Goldmann, D. *Recyclingtechnik. Fachbuch für Lehre und Praxis*, 2nd ed.; Springer: Berlin/Heidelberg, Germany, 2016. [CrossRef]
32. Krauklis, A.E.; Karl, C.W.; Gagani, A.I.; Jørgensen, J.K. Composite material recycling technology—State-of-the-art and sustainable development for the 2020s. *J. Compos. Sci.* **2021**, *5*, 28. [CrossRef]
33. Palmer, J.; Savage, L.; Ghita, O.; Evans, K. Sheet moulding compound (SMC) from carbon fibre recyclate. *Compos. Part A Appl. Sci. Manuf.* **2010**, *41*, 1232–1237. [CrossRef]
34. Pickering, S. Recycling technologies for thermoset composite materials—Current status. *Compos. Part A Appl. Sci. Manuf.* **2006**, *37*, 1206–1215. [CrossRef]
35. Hornbogen, E. Chemische und tribologische eigenschaften. In *Werkstoffe-Aufbau Und Eigenschaften von Keramik-, Metall-, Polymer- Und Verbundwerkstoffen*; Springer: Berlin/Heidelberg, Germany, 2002; pp. 220–241. [CrossRef]
36. Pillain, B.; Loubet, P.; Pestalozzi, F.; Woidasky, J.; Erriguible, A.; Aymonier, C.; Sonnemann, G. Positioning supercritical solvolysis among innovative recycling and current waste management scenarios for carbon fiber reinforced plastics thanks to comparative life cycle assessment. *J. Supercrit. Fluids* **2019**, *154*, 104607. [CrossRef]
37. Meyer, L.; Schulte, K.; Grove-Nielsen, E. CFRP-recycling following a pyrolysis route: Process optimization and potentials. *J. Compos. Mater.* **2009**, *43*, 1121–1132. [CrossRef]
38. Park, J.-M.; Kwon, D.-J.; Wang, Z.-J.; Gu, G.-Y.; DeVries, K.L. Effect of thermal treatment temperatures on the reinforcing and interfacial properties of recycled carbon fiber–phenolic composites. *Compos. Part A Appl. Sci. Manuf.* **2013**, *47*, 156–164. [CrossRef]
39. Kortmann, J. *Carbon- und Textilbetontage*; TUDALIT e.V.: Dresden, Germany, 2020; p. 17.
40. Naqvi, S.; Prabhakara, H.M.; Bramer, E.; Dierkes, W.; Akkerman, R.; Brem, G. A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. *Resour. Conserv. Recycl.* **2018**, *136*, 118–129. [CrossRef]
41. Abdallah, R.; Juaidi, A.; Savaş, M.A.; Çamur, H.; Albatayneh, A.; Abdala, S.; Manzano-Agugliaro, F. A Critical review on recycling composite waste using pyrolysis for sustainable development. *Energies* **2021**, *14*, 5748. [CrossRef]
42. López, F.A.; Rodríguez, O.; Alguacil, F.J.; García-Díaz, I.; Centeno, T.A.; García-Fierro, J.L.; González, C. Recovery of carbon fibres by the thermolysis and gasification of waste prepreg. *J. Anal. Appl. Pyrolysis* **2013**, *104*, 675–683. [CrossRef]
43. Onwudili, J.; Miskolczi, N.; Nagy, T.; Lipóczi, G. Recovery of glass fibre and carbon fibres from reinforced thermosets by batch pyrolysis and investigation of fibre re-using as reinforcement in LDPE matrix. *Compos. Part B Eng.* **2016**, *91*, 154–161. [CrossRef]
44. Yang, J.; Liu, J.; Liu, W.; Wang, J.; Tang, T. Recycling of carbon fibre reinforced epoxy resin composites under various oxygen concentrations in nitrogen–oxygen atmosphere. *J. Anal. Appl. Pyrolysis* **2015**, *112*, 253–261. [CrossRef]
45. Zhang, J.; Chevali, V.S.; Wang, H.; Wang, C.-H. Current status of carbon fibre and carbon fibre composites recycling. *Compos. Part B Eng.* **2020**, *193*, 108053. [CrossRef]
46. Nahil, M.A.; Williams, P. Recycling of carbon fibre reinforced polymeric waste for the production of activated carbon fibres. *J. Anal. Appl. Pyrolysis* **2011**, *91*, 67–75. [CrossRef]
47. Mazzocchetti, L.; Benelli, T.; D'Angelo, E.; Leonardi, C.; Zattini, G.; Giorgini, L. Validation of carbon fibers recycling by pyro-gasification: The influence of oxidation conditions to obtain clean fibers and promote fiber/matrix adhesion in epoxy composites. *Compos. Part A Appl. Sci. Manuf.* **2018**, *112*, 504–514. [CrossRef]
48. Stoiber, N.; Hammerl, M.; Kromoser, B. Cradle-to-gate life cycle assessment of CFRP reinforcement for concrete structures: Calculation basis and exemplary application. *J. Clean. Prod.* **2020**, *280*, 124300. [CrossRef]
49. Laiblová, L.; Pešta, J.; Kumar, A.; Hájek, P.; Fiala, C.; Vlach, T.; Kočí, V. Environmental Impact of Textile Reinforced Concrete Facades Compared to Conventional Solutions—LCA Case Study. *Materials* **2019**, *12*, 3194. [CrossRef] [PubMed]
50. Portal, N.W.; Lundgren, K.; Wallbaum, H.; Malaga, K. Sustainable potential of textile-reinforced concrete. *J. Mater. Civ. Eng.* **2015**, *27*, 04014207. [CrossRef]
51. Kimm, M.; Gerstein, N.; Schmitz, P.; Simons, M.; Gries, T. On the separation and recycling behaviour of textile reinforced concrete: An experimental study. *Mater. Struct.* **2018**, *51*, 122. [CrossRef]
52. Merli, R.; Preziosi, M.; Acampora, A.; Lucchetti, M.C.; Petrucci, E. Recycled fibers in reinforced concrete: A systematic literature review. *J. Clean. Prod.* **2019**, *248*, 119207. [CrossRef]
53. Scope, C.; Guenther, E.; Schütz, J.; Mielecke, T.; Mündecke, E.; Schultze, K.; Saling, P. Aiming for life cycle sustainability assessment of cement-based composites: A trend study for wall systems of carbon concrete: Dresden Nexus Conference 2020—Session 4—Circular economy for building with secondary construction materials to minimise resource use and land use. *Civ. Eng. Des.* **2020**, *2*, 143–158. [CrossRef]

54. Hatzfeld, T.; Backes, J.G.; Scope, C.; Guenther, E.; Traverso, M. Environmental assessment of carbon reinforced concrete recycling options. In Proceedings of the Fib Conference, Oslo, Norway, 12–16 June 2022.
55. Meng, F.; Olivetti, E.A.; Zhao, Y.; Chang, J.C.; Pickering, S.J.; McKechnie, J. Comparing life cycle energy and global warming potential of carbon fiber composite recycling technologies and waste management options. *ACS Sustain. Chem. Eng.* **2018**, *6*, 9854–9865. [CrossRef]
56. He, D.; Soo, V.K.; Kim, H.C.; Compston, P.; Doolan, M. Comparative life cycle energy analysis of carbon fibre pre-processing, processing and post-processing recycling methods. *Resour. Conserv. Recycl.* **2020**, *158*, 104794. [CrossRef]
57. Dong, P.A.V.; Azzaro-Pantel, C.; Cadene, A.-L. Economic and environmental assessment of recovery and disposal pathways for CFRP waste management. *Resour. Conserv. Recycl.* **2018**, *133*, 63–75. [CrossRef]
58. Dieterle, M.; Seiler, E.; Viere, T. Application of eco-efficiency analysis to assess three different recycling technologies for Carbon Fiber Reinforced Plastics (CFRPs). *Key Eng. Mater.* **2017**, *742*, 593–601. [CrossRef]
59. Nunes, A.O.; Viana, L.R.; Guineheuc, P.-M.; Moris, V.A.D.S.; de Paiva, J.M.F.; Barna, R.; Soudais, Y. Life cycle assessment of a steam thermolysis process to recover carbon fibers from carbon fiber-reinforced polymer waste. *Int. J. Life Cycle Assess.* **2017**, *23*, 1825–1838. [CrossRef]
60. Li, X.; Bai, R.; McKechnie, J. Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes. *J. Clean. Prod.* **2016**, *127*, 451–460. [CrossRef]
61. Shuaib, N.A.; Mativenga, P.T.; Kazie, J.; Job, S. Resource efficiency and composite waste in UK supply chain. *Procedia CIRP* **2015**, *29*, 662–667. [CrossRef]
62. Abdulkareem, M.; Havukainen, J.; Horttanainen, M. How environmentally sustainable are fibre reinforced alkali-activated concretes? *J. Clean. Prod.* **2019**, *236*, 117601. [CrossRef]
63. Guignot, S.; Touzé, S.; Von Der Weid, F.; Ménard, Y.; Villeneuve, J. Recycling construction and demolition wastes as building materials: A life cycle assessment. *J. Ind. Ecol.* **2015**, *19*, 1030–1043. [CrossRef]
64. Martinez-Arguelles, G.; Acosta, M.P.; Dugarte, M.; Fuentes, L. Life cycle assessment of natural and recycled concrete aggregate production for road pavements applications in the Northern Region of Colombia: Case study. *Transp. Res. Rec. J. Transp. Res. Board* **2019**, *2673*, 397–406. [CrossRef]
65. Wei, K.-Y.; Lin, J.-D.; Yu, I.-H. Assessment of {CO2} emission reduction in road construction using recycled concrete materials. *Int. J. Pavement Res. Technol.* **2013**, *6*, 423–430. [CrossRef]
66. Colangelo, F.; Navarro, T.G.; Farina, I.; Petrillo, A. Comparative LCA of concrete with recycled aggregates: A circular economy mindset in Europe. *Int. J. Life Cycle Assess.* **2020**, *25*, 1790–1804. [CrossRef]
67. Mostert, C.; Sameer, H.; Glanz, D.; Bringezu, S. Climate and resource footprint assessment and visualization of recycled concrete for circular economy. *Resour. Conserv. Recycl.* **2021**, *174*, 105767. [CrossRef]
68. Yazdanbakhsh, A.; Bank, L.C.; Baez, T.; Wernick, I. Comparative LCA of concrete with natural and recycled coarse aggregate in the New York City area. *Int. J. Life Cycle Assess.* **2017**, *23*, 1163–1173. [CrossRef]
69. Guo, Z.; Tu, A.; Chen, C.; Lehman, D.E. Mechanical properties, durability, and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates. *J. Clean. Prod.* **2018**, *199*, 136–149. [CrossRef]
70. Fraj, A.B.; Idir, R. Concrete based on recycled aggregates—Recycling and environmental analysis: A case study of Paris' region. *Constr. Build. Mater.* **2017**, *157*, 952–964. [CrossRef]
71. Kleijer, A.; Lasvaux, S.; Citherlet, S.; Viviani, M. Product-specific life cycle assessment of ready mix concrete: Comparison between a recycled and an ordinary concrete. *Resour. Conserv. Recycl.* **2017**, *122*, 210–218. [CrossRef]
72. Braga, A.M.; Silvestre, J.D.; de Brito, J. Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. *J. Clean. Prod.* **2017**, *162*, 529–543. [CrossRef]
73. Müller, C.; Reiners, J.; Palm, S. *Closing the Loop: What Type of Concrete Re-Use Is the Most Sustainable Option*; Technical Report A-2015/1860; The Concrete Initiative: Brussels, Belgium, 2015.
74. Serres, N.; Braymand, S.; Feugeas, F. Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment. *J. Build. Eng.* **2016**, *5*, 24–33. [CrossRef]
75. Turk, J.; Cotič, Z.; Mladenovič, A.; Šajna, A. Environmental evaluation of green concretes versus conventional concrete by means of LCA. *Waste Manag.* **2015**, *45*, 194–205. [CrossRef]
76. Mettke, A.; Schmidt, S.; Jacob, S. *Dokumentation zum Einsatz von Ressourcenschonendem Beton*; Senatsverwaltung für Stadtentwicklung und Umwelt: Berlin, Germany, 2015.
77. Knoeri, C.; Sanyé-Mengual, E.; Althaus, H.-J. Comparative LCA of recycled and conventional concrete for structural applications. *Int. J. Life Cycle Assess.* **2013**, *18*, 909–918. [CrossRef]
78. Weimann, K.; Matyschik, J.; Adam, C.; Schulz, T.; Linss, E.; Müller, A. *Optimierung des Rückbaus/Abbaus von Gebäuden zur Rückgewinnung und Aufbereitung von Baustoffen unter Schadstoffentfrachtung (insbes. Sulfat) des RC-Materials*; UBA: Dessau-Roßlau, Germany, 2013.
79. Heyn, S.; Mettke, A. *Ökologische Prozessbetrachtung—RC-Beton (Stofffluss, Energieaufwand, Emissionen)*; Brandenburgische Technische Universität Cottbus: Brandenburg, Germany, 2010; Volume 86.
80. Marinković, S.; Radonjanin, V.; Malešev, M.; Ignjatović, I. Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Manag.* **2010**, *30*, 2255–2264. [CrossRef]

81. Bischof, S.; Sugg, T.; Meister, R.; Grüninger, R.; Kytzia, S.; Lier, S. *Ökobilanzen Rezyklierter Gesteinskörnung für Beton*; Holcim: Zug, Switzerland, 2010.
82. Gehring, F.; Albrecht, S.; Homolka, S.; Leistner, P.; Thome, V.; Seifert, S. Aus Altbeton wird Beton-ein innovativer Recyclingansatz. *Bauphysik* **2015**, *37*, 296–300. [CrossRef]
83. *DIN EN 15804*; Nachhaltigkeit von Bauwerken-Umweltproduktdeklarationen–Grundregeln für die Produktkategorie Bauprodukte. DIN: Berlin, Germany, 2009.
84. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
85. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2008.
86. CML—Department of Industrial Ecology. CML-IA Characterisation Factors [WWW Document]. 2016. Available online: https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors (accessed on 31 July 2022).
87. Otto, J.; Adam, R. Carbonbeton und Stahlbeton im wirtschaftlichen Vergleich/Textile-reinforced concrete and reinforced concrete in an economic comparison. *Bauingenieur* **2019**, *94*, 246–252. [CrossRef]
88. Backes, J.G.; Traverso, M. Sustainability assessment of a disruptive innovation: Comparative cradle-to-gate life cycle assessment of carbon reinforced concrete. *Int. J. Life Cycle Assess.* 2022; *submitted*.
89. Klingler, M.; Savi, D.; Gabor, D. Harmonisierte Ökobilanzen der Entsorgung von Baustoffen—Für die Liste der Ökobilanzdaten im Baubereich. 2021. Available online: www.umweltchemie.ch (accessed on 31 July 2022).
90. Schröder, M.; Pocha, A. *Abbrucharbeiten*, 3rd ed.; Verlagsgesellschaft Rudolf Müller GmbH & Co. KG: Köln, Germany, 2015.
91. Notter, B.; Schmied, M. *Energieverbrauch und Schadstoffemissionen des Non-road-Sektors: Studie für die Jahre 1980–2050*; Bundesamt für Umwelt: Bern, Switzerland, 2015.
92. Müller, A. *Baustoffrecycling-Entstehung-Aufbereitung–Verwertung*; Springer: Wiesbaden, Germany, 2018. [CrossRef]
93. Manouchehri, H.-R. Application of optoelectronic sorting technique for upgrading minerals and wastes. In Proceedings of the Konferens i Mineralteknik, Luleå, Sweden, 7–8 February 2006. Föreningen Mineralteknisk Forskning/Swedish Mineral Processing Research Association.
94. Hedlund-Åström, A. Model for End of Life Treatment of Polymer Composite Materials. Ph.D. Thesis, School of Industrial Engineering and Management (ITM), Stockholm, Sweden, 2005.
95. Gutowski, T.; Dahmus, J.; Thiriez, A. Electrical energy requirements for manufacturing processes. In Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium, 31 May–2 June 2006.
96. Hengstermann, M. *Entwicklung von Hybridgarnen aus Recycelten Carbonfasern und Polyamid 6-Fasern für Thermoplastische Verbundbauteile mit Hohem Leistungsvermögen*; Universität Dresden: Dresden, Germany, 1986.
97. Hartz, A.; Schniedermeier, L.; Saad, S.; Manderla, B. *Mittel-und Langfristige Sicherung Mineralischer Rohstoffe in der Landesweiten Raumplanung und in der Regionalplanung*; MORO Praxis: Berlin, Germany, 2017.
98. *DIN EN 12620*; DAfStb Beton rezyklierte Gesteinskörnung, DAfStb-Richtlinie Beton nach DIN EN 206-1 und DIN 1045-2 mit rezyklierten Gesteinskörnungen Nach. DIN: Berlin, Germany, 2010.
99. *DIN 4226-101*; Deutsches Institut für Normung (DIN) e.V. DIN: Berlin, Germany, 2017.
100. *DIN EN 12620*; Deutsches Institut für Normung (DIN) e.V. DIN: Berlin, Germany, 2008.