



# Article of RILEM TC 292-MCC: life cycle assessment (LCA) of non-metallic reinforcement for reinforcing concrete: manufacturing, durability, dismantling, recycling and reuse: a review

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**Abstract** The potential of non-metallic reinforcement to be an environmentally sustainable alternative to classic steel reinforcement in concrete has become evident in recent years. The high-performance fibres used to produce non-metallic reinforcement elements have a considerably lower weight to transferable tensile forces ratio and are almost non-corrosive under common exposures. These indicators allow for a high environmental performance throughout the extended life cycle of the product. At the same time,

substantially more resources and energy per unit weight are required for their production in some cases, e.g. for carbon fibres, compared to conventional reinforcing steel. The presented work addresses this conflict by closing a number of obvious research gaps. Despite an increasing number of publications during the last years, so far there are no comprehensive sets of data available on the environmental impact of various concrete reinforcing materials. With the data compiled in this work, for the first time, an objective comparison of different reinforcement systems (conventional and alternative) is presented that differentiates various environmental impact categories and therefore enables to perform Life Cycle Assessment (LCA). Other often observed shortcomings in sustainability assessments in concrete constructions are that an extension of the service life due to improved durability and the burden a material poses at the end of its life

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cycle are not considered. Comprehensive reviews of durability considerations help to develop an estimation of the service life. In addition, a state-of-the-art on possible strategies for dismantling, recycling and reuse of alternative non-metallic reinforcement systems shows that the composition of the FRPs, i.e., fibre and matrix materials, not only has a strong influence on the environmental impact in the production phase, but also on the durability as well as on a possible reuse.

**Keywords** Life cycle assessment · Concrete structures · Non-metallic reinforcement · Fibre reinforced polymers · CFRP, BFRP, GFRP · Resource efficient building construction

## 1 Introduction

The construction industry, especially the concrete sector, uses a considerable portion of the natural resources extracted from the lithosphere, consumes a massive amount of the total energy and is responsible for a major part of the solid waste [1]. It is estimated that the concrete construction is responsible for 8% to 9% of the global CO<sub>2</sub> emissions [2, 3] and forecasts point to a further increase of up to 12%. Thus, it is inevitable to look for alternative solutions to reduce the amount of material and energy required for the construction of buildings and infrastructure as well as to find solutions for an ideally lossless reuse of the materials after the demolition of these structures.

Fibre reinforced polymers (FRP) have a high tensile strength and, in comparison to steel reinforcement, a considerably higher tensile strength to unit weight ratio [4, 5]. In addition, their performance under common corrosive exposures is superior, which results in a longer service life in comparison to conventional steel reinforced concrete (RC) structures. This leads to the expectation of a high potential for their use as reinforcement in concrete structures, at least in certain applications. However, the assessment of the environmental impact over the whole life cycle requires additional knowledge about the production, the durability, as well as the dismantling and end-of-life fate [6]. Since recycling and possible reuse options are not yet satisfactorily investigated, the present compilation as a review paper presents a comprehensive picture of the state of the art and identifies a solid basis for further research.

This article consists of several parts that address the state of knowledge in addition to a short introduction and a summary of conclusions. Section 2 deals with the Life Cycle Assessment (LCA) fundamentals and provides an overview of the literature regarding LCA of structures containing FRP reinforcement used in the construction and transportation sectors. Section 3 is an overview of the state of knowledge on the environmental impact of different FRP materials from cradle to gate for chosen impact categories focusing on their use as reinforcement for concrete structures. Basic calculation values (per kg) are provided and compared to conventional reinforcement as well as prestressing steel. Section 4 gives an overview of the durability of FRP reinforcement elements. Section 5 summarises the state of knowledge regarding dismantling, recycling and reuse of concrete structures reinforced with different FRPs, with a special focus on the processing of the FRP reinforcement.

## 2 State of the art in LCA specific for FRPs

Several LCA studies on the use of FRP composites in construction have addressed various perspectives [8–14]. The current state-of-the-art studies on LCA show the processes for assessment of the environmental performance and comparison of different products [14]. According to ISO 14040/44, a LCA assesses the environmental impacts of a product along its life. It can lead to different results depending on the goal and scope defined (ISO 14040:2006 + A1:2020; ISO 14044:2018 + A1:2020). In some cases, Life Cycle Costing (LCC) is realised in addition to the LCA, allowing for a measurement of the costs and revenues obtained in the product life cycle. The LCC analysis is an important complementary methodology to the LCA and allows the identification of trade-offs between the two pillars of sustainability: the economic one and the environmental one. A combination of LCA and LCC over the entire life cycle has been used on FRP dating back to 2005–2006, with a primary focus on the transportation sector and LCC [15]. A considerable increase of interest in LCA has been noted over the last few years. Publications are divided into two main fields: Those focusing only on the LCA and those combining LCA and LCC. Special attention has been placed on bridges or their sub-structures. A review of LCA applied to concrete beams was presented at the



International Conference on Civil Infrastructure and Construction (CIC 2020).

Table 1 presents a small selection of studies (LCA and LCC) that include research that extends to recycling within the building sector only. Studies dealing with LCA and FRP that originate from the automotive or aerospace sector, or dealing purely with recycling, which are detached from the building sector, are not considered.

The table shows that one is far from having a harmonized implementation of the LCA methodology to the CFRP, indeed differences can be identified in the system boundaries (cradle-to-grave which include the entire life cycle of a product from extraction of raw materials to end of life, or cradle-to-gate which is from raw material extraction to the manufacturing of the final product) in the functional units used and in the different service lifespans considered.

Even if the ISO 14040 clearly suggests the necessity to assess the environmental impacts of a product along its entire life cycle, most of the studies (as shown in Table 1) are focusing on cradle-to-gate systems. One study [9] did not explicitly name the system boundaries.

Table 1 also shows that the Functional Units (FUs), which define the quantified performance of a product (ISO 14040), differ considerably. It is also clear that the interpretation of lifetime varies greatly. Some studies consider the lifetime, while others do not mention this aspect at all. A closer look at the LCIA of the studies shows that all studies include Global Warming Potential (GWP) which defines the impact on climate changes. Furthermore, 14 of the 21 studies use the midpoint indicator Acidification Potential (AP). The indicators Eutrophication Potential (EP) and Ozone Depletion Potential (ODP) were named 11 times, closely followed by Photochemical Oxidant Creation Potential (POCP) (10x), Abiotic Depletion Potential (fossil) (ADP<sub>f</sub>), Human toxicity potential and Freshwater Aquatic Ecotoxicity (FAET). All other indicators such as Cumulative Energy Demand (CED), Particulate Matter or Water Resource Depletion were named in less than 5 studies. It is noticeable that in many studies absolute values are not specified or shown. Often percentages are used or graphs are shown, which makes a direct comparison between the results of different studies impossible.

### 3 Cradle-to-gate LCA of FRP reinforcement: environmental range of different non-metallic reinforcement types

Currently, LCA data for FRP reinforcement for concrete structures is only available to a modest extent. This section summarizes available properties and data as a basis for the evaluation of the estimated environmental impact of different reinforcement materials. The first part gives a brief overview of the properties and possible application of FRP reinforcement. Subsequently, selected cradle-to-gate LCA data is identified to provide the user with an estimation of the environmental impact of FRP reinforcement within the design of FRP reinforced concrete structures. At the end of the section, the environmental impacts for 1 kg of different reinforcement materials as well as for the transmission of equal tensile forces are given. This data should highlight the performance of different reinforcement types in conjunction with their environmental impacts.

#### 3.1 Properties of FRP reinforcement

Reinforcement elements made from FRPs have a higher specific tensile strength, and depending on the fibre and matrix material, a higher resistance against corrosion as compared to conventional reinforcing steel. This allows for a reduction of the concrete cover and consequently of the building component dimensions and weight. Furthermore, it is advantageous for the service life of structures with a high exposure to chloride ions as for example bridges and parking structures. FRP can be produced by combining different material combinations. Usually alkali resistant glass (AR glass), carbon, basalt or aramid are used as fibre material. Epoxy resins, rubber-based systems dispersed in water (e.g. styrene-butadiene) or acrylate-based systems are the most frequently used matrix materials. Chosen material properties of AR glass fibre reinforced plastic (GFRP), carbon fibre reinforced plastic (CFRP) and aramid fibre reinforced plastic (AFRP) reinforcement elements can be found in [33]. The mechanical properties vary widely by the use of different combinations of fibre and matrix -materials [34]. GFRP, AFRP and basalt fibre reinforced plastic (BFRP) as concrete reinforcement tend to exhibit higher tensile strength, but lower stiffness in comparison to conventional reinforcing steel. CFRP

**Table 1** Analysed papers focusing on LCA of FRPs

Author	Year	Product	Scope	Functional unit	Service life in years	LCA	LCC
Mara et al. [9]	2013	four different bridge design alternatives; a conventional steel–concrete composite bridge and three steel bridges with fibre reinforced polymer (FRP) deck	Not specified	Road bridge with four traffic lanes, pedestrian area and a life span of 100 years	100	X	X
Princaud et al. [16]	2014	supercritical fluid technology applied to CFRPs recycling	Cradle-to-grave	1 kg of carbon fibre/CFRP	–	X	
Pang et al. [17]	2015	highway bridge with four different strengthening plans	Cradle-to-grave	1 m unit length of the bridge system in the longitudinal direction with a life span of 100 years	100	X	
Maxineasa [18]	2015	comparing non-strengthened reinforced concrete (RC) beam with carbon fibre-reinforced polymer (CFRP) flexural strengthening techniques	Cradle-to-gate	Reinforced concrete beam + carbon strips	–	X	
Williams Portal et al. [19]	2015	protective design cover mandated for reinforced (textile) concrete facades	Cradle-to-gate	1 m <sup>2</sup> of reinforced concrete	–	X	
Inman et al. [11]	2017	comparison of Basalt Fibre Reinforced Polymer (BFRP) rebar and steel rebar in concrete beams	Cradle-to-gate	BFRP concrete beams	–	X	
Palacios Muñoz et al. [20]	2018	simplified structural design and LCA of reinforced concrete beams strengthening techniques	Cradle-to-gate	Particular increase in the bending capacity of a specific reinforced concrete beam	–	X	
Maxineasa et al. [21]	2018	producing an RC beam and strengthening an existing RC beam using CFRP and GFRP	Cradle-to-gate	1 kg of material & 6 cases of strengthening solutions with different resulting load capacities	–	X	
Nunes et al. [22]	2018	recycling carbon fibres from CFRP waste by steam thermolysis	Cradle-to-grave	2 kg of composite (1 kg of long fibre composite and 1 kg of short fibre composite)	10 (only for production equipment)	X	
Garg, Shrivastava [23]	2019	different FRP's rebars as a substitute to traditional steel rebars in RC beam	Cradle-to-gate	Ultimate moment carrying capacity (Mu) MU/m <sup>3</sup> and Mu/kg	–	X	X
Pillain et al. [24]	2019	comparing CFRP recycling scenarios (pyrolysis, supercritical solvolysis, electrodynamic fragmentation) with landfilling and incineration	Cradle-to-grave	Managing the end of life of 1 kg of CFRP composed of 60 wt% carbon fibres and 40 wt% epoxy resin	–	X	
Cadenazzi [12]	2019	alternative materials for bridge: Carbon Steel (CS); Epoxy-Coated Steel (ECS); Stainless Steel (SS); and Fibre Reinforced Polymers (FRP)	Cradle-to-gate	Bridge construction	75–100	X	X



**Table 1** continued

Author	Year	Product	Scope	Functional unit	Service life in years	LCA	LCC
Cadenazzi [25]	2020	fiber-reinforced polymer-reinforced concrete bridge in Florida	Cradle-to-grave	FRP-RC/PC bridge	100	X	X
Chen [26]	2020	natural (unidirectional flax, woven jute) and carbon-FRP strengthening methods	Cradle-to-grave	CFRP: 1.2-g carbon fabric and 0.5-g epoxy resin	–	X	X
Demertzi, Silvestre, Duraó [27]	2020	composite sandwich panels	Cradle-to-grave	1 linear meter (LM) of floor, produced by pultrusion with 0.5 m width; in the case of PUR and SFRMC: 1 m <sup>3</sup> ; in the case of the finished panels: 1 LM (without PUR and SFRMC) and 1 m <sup>2</sup> (finished)	–	X	
Scope et al. [28]	2020	4 variants of sandwich wall systems: 2 each made of SRC (steel) and CCC (carbon)	Cradle-to-grave (w/o use-phase)	Sandwich wall system	50	X	X
Akbar, Liew [29]	2020	recycling of CFRP waste and the effects of recycled carbon fibres (rCFs) as reinforcement	Cradle-to-grave	1 m <sup>3</sup> of cement composite (scenarios: 1% of recycled carbon fibres vs. 1% of virgin carbon fibres)	25	X	
Stoiber, Hammerl, Kromoser [6]	2021	CFRP reinforcement in concrete structures	Cradle-to-grave	1 kg of the particular product (epoxy resin, carbon fibre, CFRP reinforcement, steel product) and one cubic meter of concrete		X	
Dong, Li, Xian [30]	2021	three kinds of beams (GFRP/CFRP bar-reinforced SWSSC beams, and steel bar-reinforced common concrete (SRC) beam) in marine environments	Cradle-to-grave	Beam that meets the requirements of both strength and serviceability	–	X	
Xiong et al. [31]	2021	feasibility of collaborative use of recycled discarded tires and CFRP waste called recycled CFRP fibre reinforced rubberized concrete (RFRRC)	Cradle-to-grave	4 FUs can be adopted: volume, combining volume and strength, considering volume strength and durability simultaneously, and strength reliability	–	X	
Stoiber, Hammerl, Kromoser [32]	2021	FRP reinforcement in concrete structures	Cradle-to-grave	1 kg of the particular product (different resins, different fibre types)		X	

reinforcement usually has a slightly lower or similar stiffness and a significantly higher tensile strength compared to conventional reinforcing steel.

In comparison to reinforcing steel, which exhibits ductile failure at its load limit due to elasto-plastic

material behaviour (yielding), FRP reinforcing elements exhibit linear-elastic material behaviour with ultimate brittle failure. In general, the very good mechanical properties in the longitudinal direction of the fibres are contrasted by brittle direct tensile



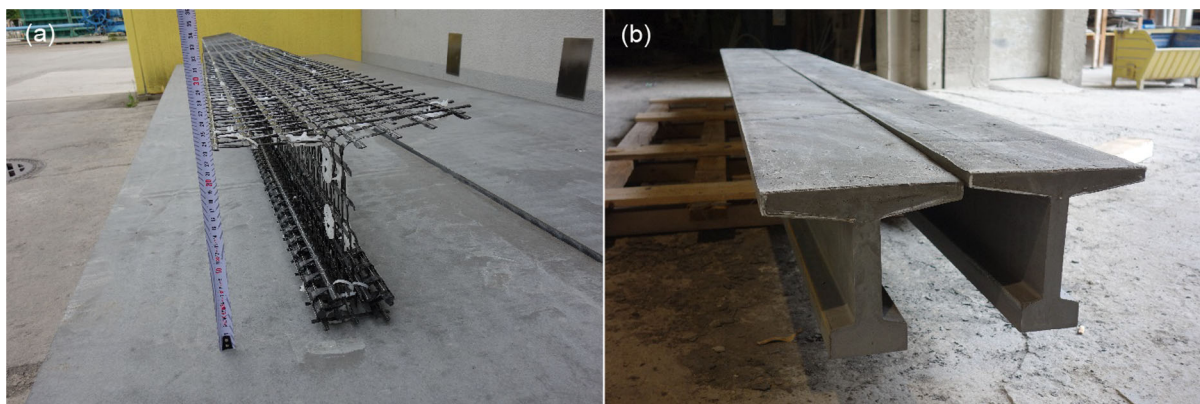
behaviour of the unidirectional continuous fiber composite. A required ductility can only be provided within this linear elastic range in combination with a cracking of the concrete structure. This has to be considered when used in seismic areas.

FRP reinforcement is available in the form of textile reinforcement elements, bars and strands. Although ideas to use FRP as concrete reinforcement go back a long time, it is still a young field both with respect to research and application in the practice of construction. A compilation of already realised projects can be found in [35], while [37–39] provide examples of a free-formed shell roofing and two different pedestrian and bicycle bridges. Currently, non-metallic reinforcement is being researched in a number of projects worldwide on a wide variety of topics. Considerable efforts are taken to develop guidelines, codes and test methods, for example in the ACI committee 440 “Fiber-Reinforced Polymer Reinforcement” or efforts regarding the new Annex JA in Eurocode 2 for internal FRP reinforcement which will be considered in the new version. Numerical and experimental investigations of the bending and shear strength of thin-walled CFRP reinforced UHPC components for building construction are described in [4, 6, 40]. A FRP reinforcement cage and two beam elements are shown as examples in Fig. 1.

In the case of FRP reinforcement, a good bond with the concrete is a challenge, since the surfaces of bars and textiles are usually smooth since the fibres are oriented in longitudinal direction. This is especially true for rods and strands which are mostly produced by pultrusion. Possibilities for improving the bond properties are subsequent sanding, milling of ribs or a

subsequent application of a rib in the form of a thread or roving. Investigations on the composite load-bearing behaviour of subtractive machined CFRP rods in UHPC are described in [40]. Insights about the bond behaviour of textiles are provided in [42–44] where an early delamination of the concrete cover as a failure mechanism is observed in certain cases. A comprehensive categorical investigation of the different influencing parameters is still missing, as is the case for bars and strands. Furthermore, in comparison to conventional steel reinforcement, the internal bond between fibres and polymer matrix material is decisive in addition to the bond between concrete and reinforcement.

The use of non-metallic reinforcement is often justified with environmental advantages. However, from an objective point of view, the low density and the good mechanical properties in terms of tensile strength of FRP reinforcement are partly offset by the significantly higher environmental impact than steel as well as the significantly higher energy consumption than steel during production per unit of mass. In addition, their modulus of elasticity values can be lower than conventional reinforcement steel. The higher environmental impact is particularly true for CFRP reinforcement, with the production of carbon fibres being the most influential component. The lower modulus of elasticity concerns GFRP and BFRP and, in many cases, CFRP too. Objective comparisons of the environmental efficiency are currently barely available, as already mentioned in Sect. 2. Potential reasons for this are (a) a relatively low interest in such comparisons, (b) a large number of influencing parameters in the course of planning and production



**Fig. 1** **a** Reinforcement cage made of CFRP and **b** completed CFRP reinforced ultra-high performance concrete beam (UHPC) [4]

of components (material-structure-manufacturing), (c) limited availability of data on fibre production, and (d) proprietary nature of materials and production methods of polymeric fibre composites.

### 3.2 Selected cradle-to-gate LCA data

Table 2 shows selected available environmental impact indicators of different fibre and matrix materials. As the boundary conditions (e.g. underlying Life Cycle Impact Assessment method) of the available studies vary widely, the authors decided to mention several individual sources instead of giving a range. In that way, the transparency of the data and related statements is preserved. Table 3 shows a number of environmental impact indicators and, if available, the energy demand for the production phases (according to EN 15804: A1–A3) of reinforcing rods and textile reinforcing elements made of FRPs. As a basis for the calculation, a fibre/matrix proportion of 60/40% for the bars and 55/45% for textile reinforcing elements was assumed. The environmental impact parameters (GWP, AE and energy demand) according to EN

15804 for basalt fibres and glass fibres are roughly one order of magnitude smaller than those of epoxy resin, leading to a significantly lower influence on the overall balance. For these two types and impact indicators, the matrix material is therefore decisive when using epoxy resin. A similar picture emerges for the other matrix materials, although not that pronounced. The environmental footprint of carbon fibres is more than 20-fold higher than that of the other two fibre types and four times higher than that of epoxy resin. For CFRP, the carbon fibre content is, therefore, decisive for the overall balance. It has to be highlighted that the statements made above must be considered in the context of the available data and their uncertainties.

### 3.3 Environmental impact vs. transferable tensile forces

CFRP has better properties than GFRP and BFRP in terms of tensile strength and stiffness (compare with Table 4), but is associated with a much higher environmental footprint. In comparison to reinforcing steel, the GWP of GFRP or BFRP is about 1.5 to 2

**Table 2** Selected impact indicators for the manufacturing phase (A1–A3) of different fibre materials and epoxy resin as matrix material (Functional unit: 1 kg)

Material	Source	GWP (kg CO <sub>2</sub> -eq.)	ODP (kg CFC11-eq.)	AE (mol H +eq.)	EP-freshwater (kg P-eq.)	ADP non-fossil (kg Sb-eq.)	Energy demand* (MJ)
Glass fibres	[47] (direct roving)	1.18	–	4.66E–03	3.44E–04	1.95E–06	23.5
	[48]	1.3	–	–	–	4.20E–07	24.5
	[49] (direct roving)	1.36	5.80E–08	2.86E–03	2.38E–05	1.63E–05	17.7
Carbon fibres	[50]	26.4	–	–	–	1.20E–05	454.0
	[49]	49.1	1.84E–05	2.10E–01	3.10E–03	2.32E–04	1040.9
Basalt fibres	[51] (production Iceland, electricity)	0.15	4.63E–08	–	–	8.84E–04	–
	[51] (production Russia, electricity + gas)	1	2.40E–07	–	–	2.05E–02	–
Epoxy resin	[49]	6.73	1.78E–09	5.09E–02	4.07E–05	9.91E–06	135.0
	[52]	8.6	–	–	–	–	–
Vinyl ester resin	[49]	5.97	1.34E–07	3.49E–02	1.35E–04	1.01E–04	121.5
Polyester resin	[49] (unsaturated)	3.94	5.13E–07	1.65E–02	1.15E–04	7.24E–05	87.9
Styrene-butadiene rubber	[53]	1.2	–	–	–	1.66E–02	38.1
Acrylate dispersion	[53]	1.7	–	–	–	1.53E–02	36.6

**Table 3** Selected impact indicators for the manufacturing phase (A1–A3) of FRP rods and textiles (FU: 1 kg), Note: the cells of Table 2 highlighted in orange served as a calculation basis for the presented results [54]

FRP type	Rod/textile	GWP (kg CO <sub>2</sub> -Äq.)	AE (mol H + -Äq.)	ADP non-fossil (kg Sb-Äq.)	Energy demand* (MJ)
GFRP	Rod	3.4	2.32E-02	5.13E-06	6.81E + 01
	Textile	3.7	2.55E-02	5.53E-06	7.37E + 01
CFRP	Rod	32.2	1.46E-01	1.43E-04	6,79E + 02
	Textile	30.0	1.38E-01	1.32E-04	6,33E + 02
BFRP	Rod	3.3	–	1.23E-02	–
	Textile	3.6	–	1.13E-02	–

**Table 4** Simplified assumptions for the characteristic tensile or yield strength of different FRP reinforcement elements, prestressing steel and conventional reinforcing steel [54]

	GFRP rod (MPa)	GFRP textile (MPa)	BFRP rod (MPa)	BFRP textile (MPa)	CFRP rod (MPa)	CFRP textile (MPa)	Prestressing steel (MPa)	Reinforcing steel (Austria) (MPa)
Characteristic tensile or yield strength	1200	1000	1200	1400	2100	2300	1660	550

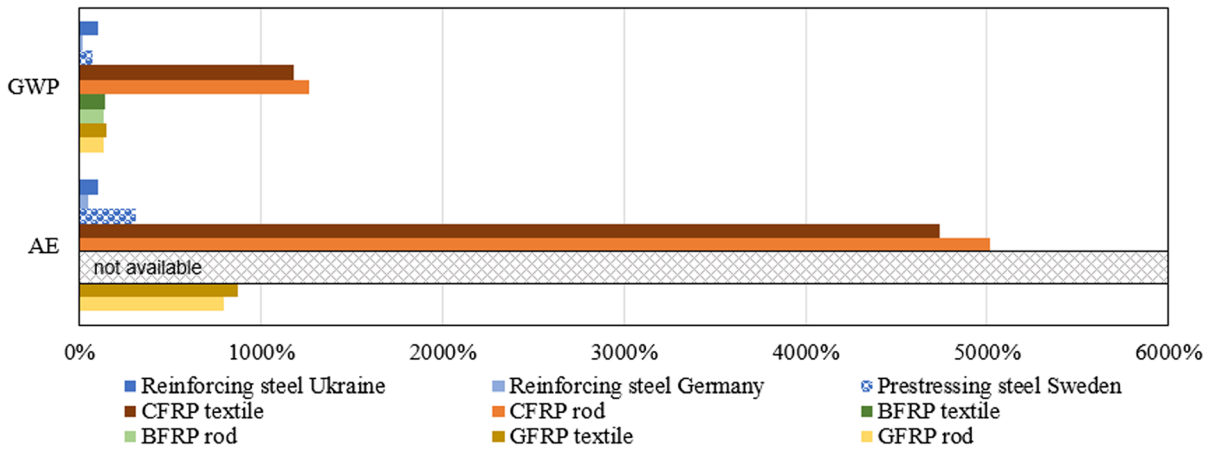
times higher in the present analysis with the available data base, which is approximately the ratio of the corresponding tensile strength values. Compared to conventional reinforcing steel, CFRP has a significantly higher environmental footprint per unit weight, even when considering the high tensile strength. In this context, a recently published EPD of a CFRP textile (solidian GRID Q85-CCE-21) as well as a GFRP rod (solidion REBAR D14-RRE) product can be mentioned. The fibre/matrix proportion of the CFRP textile product is approximately 60/40%, as also assumed within the present study (compare with Table 3) with epoxy resin as matrix material. The proportion of the GFRP rod product, however, is different with a ratio of around 85/15%. The environmental impact indicators presented in Table 3 tend to be slightly higher than of the specific products provided by solidian [44], thus, underpinning the validity of the data presented herein.

The available data was combined to a comprehensive comparison of potential with simplified assumptions. Figure 2 shows the standardised environmental impact per kg of reinforcement for different types of reinforcement (steel and FRP). The high influence of the efficiency of the steelmaking process is evident as a comparison of producers in different countries shows, e.g. with lower values in case of Germany and higher values (even up to 5 times in case of the GWP) in Ukraine. Furthermore, the comparisons show

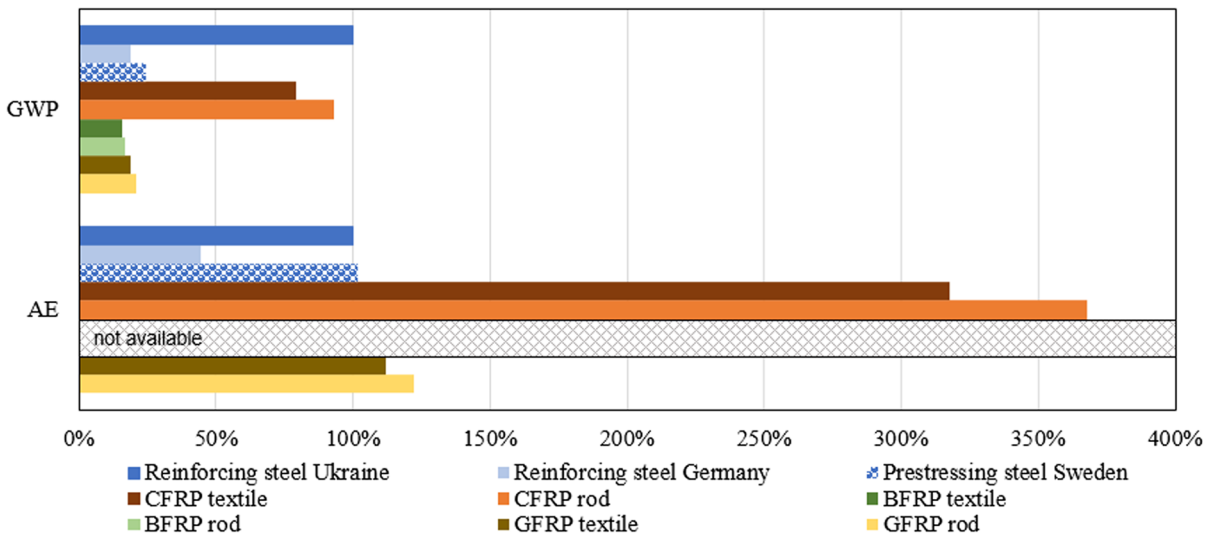
the very high environmental impact of the carbon fibres. If the density of the materials (7850 kg/m<sup>3</sup> for reinforcing steel and prestressing steel and 2200 kg/m<sup>3</sup> for all FRP reinforcement elements) and the characteristic tensile strength is taken into account, a clearer picture regarding the environmental potential of the different types of reinforcement is obtained (see Fig. 3). In this respect, clear advantages can be seen for GFRP and BFRP, whereby the low stiffness makes large-scale application difficult with regard to the serviceability criteria (maximum acceptable deformations). A possible remedy or necessary supplement is the use of prestressing under the assumption that the component dimensions can be reduced [45, 46]. In [6] a comparison of different bridge structures was carried out. Part of the analysis was a bridge reinforced exclusively with CFRP, a reinforced concrete bridge and a steel bridge, which are used as foot and cycle path overpasses and have very similar dimensions and payloads. In an exclusive consideration of the manufacturing phase, the CFRP reinforced bridge showed advantages in the impact categories GWP and ADP fossil and disadvantages in the category AP (Acidification Potential). If the service life can be increased by the CFRP reinforcement due to its high corrosion resistance, the advantage becomes even clearer.

Environmental data on the life cycle phases of FRP reinforcement post production and use stage are barely





**Fig. 2** Normalised environmental impact (GWP and AE) for the manufacturing phase (A1–A3) of 1 kg of different reinforcement elements and materials



**Fig. 3** Normalised environmental impact (GWP and AE) of different reinforcement materials per unit volume related to their tensile strength values

available, with the EPD of the GFRP rod and CFRP textile product by solidian mentioned above provided as one rare example. It gives data of the end of life stage C1-C3 as well as benefits beyond the system boundary D. Generally, in this EPD impact indicators of life cycle stages C1-C3 represent only fractions when compared to the respective production stage A1-A3. Regarding the GFRP rod product, landfill is defined as end of life scenario. As the carbon fibres are assumed to be entirely recycled, in stage D of the CFRP textile product rather high negative values (equals savings) for the impact indicators GWP, ADP

fossil and the energy demand are listed. However, the extent to which the latter is only a theoretical scenario needs to be questioned.

#### 4 Use phase: durability of non-metallic reinforced concrete structures

This section gives an overview of the durability of concrete structures with non-metallic reinforcement made of basalt, AR glass, or carbon fibres. For a comprehensive LCA of concrete structures, an

appropriate estimation of their service life under different exposures is of great importance. The intended significantly longer service life of concrete with non-metallic reinforcement is therefore an essential instrument to ensure a positive LCA balance compared to conventional reinforced concrete structures.

The durability of concrete structures with non-metallic reinforcement is determined by the durability of its structural components: non-metallic reinforcement, concrete matrix and the properties of interphase between them. In the subsequent subsections, the durability of these components is assessed separately. The focus is set on the non-metallic reinforcement.

#### 4.1 Durability of non-metallic reinforcement

##### 4.1.1 Fibre bulk material

*4.1.1.1 Filaments made of glass or basalt* Glass fibres and basalt fibres are inorganic, non-metallic materials that are a supercooled melt in terms of their structure. Since the energy level of such amorphous, glassy structures is slightly higher than that of crystalline structures, they generally show a tendency to crystallise or devitrify.

Glass fibres and basalt fibres show high resistance to a variety of chemical attacks. However, in alkaline aqueous solutions,  $\text{OH}^-$ -ions from the surrounding solution react with the network formers of the amorphous structure and form low-molecular, soluble silicates. Since a diffusion-limiting silicate layer fails to form to slow down the rate of reactions, this corrosion mechanism follows a constant rate. The rate of corrosion is significantly influenced by the chemical composition of the glass or basalt, the intensity of the chemical attack, and the temperature [55].

Besides the latent chemical attack, mechanically loaded glass or basalt fibres are also subject to coupled physical–chemical attacks by stress-dependent, chemical reactions at surface defects. Stress and strain singularities arise at such flaws under mechanical load, so that crack corrosion occurs with particularly high intensity at these spots. In addition to the mechanical stress, the temperature also has a significant influence on the fibre's local rate of corrosion at the flaws.

In the case of glass fibres, the addition of  $\text{ZrO}_2$  can significantly reduce the corrosion progress in alkaline environments. Calcium ions from the pore solution

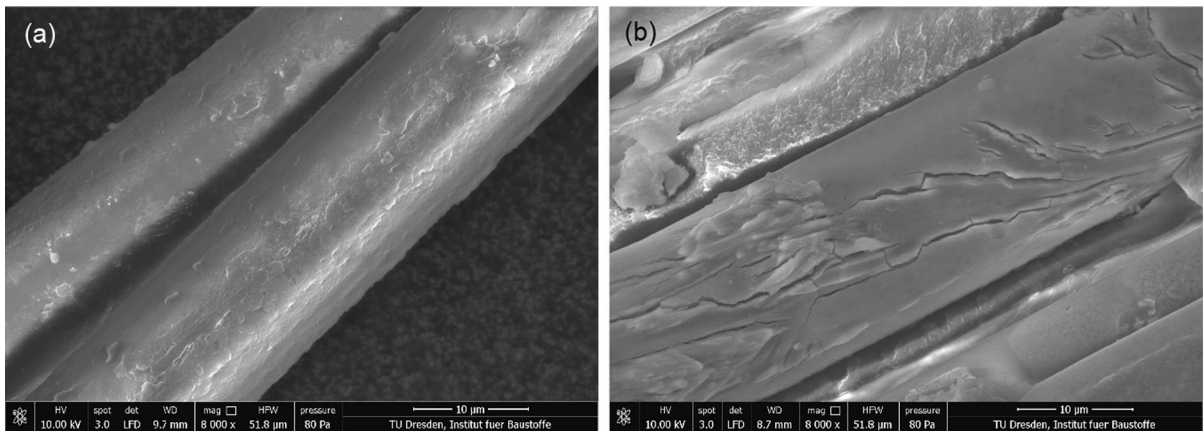
and  $\text{ZrO}_2$  from the glass bulk form a nearly insoluble reaction layer at the filament's rim which increasingly hinders the diffusion of  $\text{OH}^-$ -ions. Hereby the effectiveness of the protective layer depends on the calcium content of the corrosion medium. Glass fibres which have such a protective mechanism are called alkali resistant (AR) glass fibres as already introduced above. The resistance of the glass in an alkaline environment rises with increasing  $\text{ZrO}_2$  content. At contents over 20 wt.%, the viscosity of the melt, the melting temperature as well as the tendency to segregation and crystallisation increase significantly, so that the  $\text{ZrO}_2$  content of AR glass fibres is usually limited to 20 wt.%.

A relatively high content of naturally present metal oxides provides a higher alkali resistance to basalt fibres compared to glass fibres but considerably lower resistance in comparison to AR glass. No significant work has been conducted to address the chemical modification of basalt fibre melt with the aim of increasing its corrosion resistance in concrete [56].

A significant delay of alkaline attack can be achieved by applying a coating to the fibre surface [55]. The coating reduces the diffusion rate of ions and water. The polymers applied in the course of fibre spinning are called sizing. The main component of the sizing is a film former which acts as a surface protection and diffusion barrier. It also promotes filament cohesion in the yarn. Furthermore, adhesion promoters which are supposed to control the chemical coupling between fibre surface, sizing and matrix are also included. In experiments on Na-Ca-glass with sizing based on acrylate, epoxy or silicone, its protective effect was shown by significantly less corrosion on treated glasses. A similarly protective effect of sizing can be assumed for basalt fibres [57]; see Fig. 4.

*4.1.1.2 Filaments made of carbon* Carbon fibres consist of turbostratically arranged hexagonal graphite structures. Turbostratic means, the plane arrangement of graphite layers becomes twisted, branched, split and linked during fibre production. In the basal plane of the graphite structure, strong covalent bonds act between the C atoms. Thus, at normal temperatures and pressures, carbon fibres show no corrosion phenomena for a wide range of chemical attacks. The basal layers are interconnected by low van der Waals forces as well as by the turbostratical structure





**Fig. 4** Identical basalt fibres with different sizing after 360 days storage in readjusted pore solution, pH 13.5: **a** no visible damage of fibre, sizing slightly damaged; **b** severe damage of fibre, destruction of fibre body

[58]. Considering the basic statements of the Pourbaix diagram [59], carbon fibres do not corrode in aqueous environments at values below pH 13 and in the absence of oxidising substances. But this window of stability is quite narrow and is lost when the electrode potential of carbon is shifted. Depending on the pH value, oxidation can occur when the electrode potential is increased (formation of e.g.  $\text{CO}_2$ , carbonic acid ( $\text{H}_2\text{CO}_3$ )). If the electrode potential is reduced, a reduction can take place (formation of e.g. methane or other organic substances). Both types of conversions (oxidation and reduction) are possible with regard to the energy balance, but are primarily theoretical cases [59].

Immediately after production, carbon filaments have a non-polar, inert surface due to their quasi-perfect hexagonal in-plane structure. In order to allow the filaments to interact with a matrix, a sizing is applied here as well. Before the sizing is applied, the filament surface is activated e.g. by electrochemical processes. The activation enables the wetting with the sizing and its permanent covalent bonding on the carbon filament surface [58].

**4.1.1.3 Composites made of fibre and polymer impregnation (fibre reinforced polymer—FRP)** In cementitious composites, the individual reinforcing fibre filaments are not usually immersed in sizing, but as filament bundles in which the individual filaments interact mechanically. The filament bundles can be short (chopped strand) or continuous (roving). Rovings can be processed into textile reinforcement

structures, reinforcement bars and strands as introduced above.

These filament bundles/rovings are created by impregnating the yarn with a polymer. Common polymer impregnations are epoxy resins, rubber-based systems dispersed in water (e.g. styrene-butadiene) or acrylate-based systems. For rebars produced by pultrusion processes, resin systems are used which cure quickly when heated.

The main functions of impregnation are manifold.

1. The impregnation ensures the bond between the individual filaments in the roving. The filaments during the yarn production are present with undulations and unequal lengths, which result in varying degrees of strain/stress when the yarn is subjected to tensile forces. The cured impregnation homogenises the stress distribution over the yarn's cross-section. As a result, the impregnation is not only subject to the global unidirectional stress state of the fibre-impregnation composite, but also experiences local distortions between the filaments. The resulting stress state in the impregnation leads to visco-elastic deformations of the polymer impregnation. Cracks may occur in the impregnation and in the interphases between the impregnation matrix and the filaments; see [60].
2. The impregnation defines the chemical, physical and morphological properties of the surface of the FRP and thus determines the characteristics of the bond to concrete [58, 59]. For example, epoxy resin surfaces show a low affinity to the hydration products of the cement, thus forming only a low

chemical/adhesive bond. However, the relatively high strength and stiffness of cured epoxy enable the activation of positive-locking components resulting from structural or random cross-sectional changes of the reinforcement element.

3. The impregnation forms a diffusion barrier against the access of chemicals to the filament surface. This aspect is of paramount importance when basalt fibre or non-AR-glass fibres are used, as they do not exhibit sufficient resistance in the alkaline environment. For carbon fibres that are inert in concrete under normal conditions, the protective effect of impregnation is irrelevant. The diffusion barrier properties of impregnations mainly depend on the material composition, the layer thicknesses, presence of defects/cracks as well as the ambient temperature.

The durability of FRP with thermoset matrices at various humidity and temperature conditions and at specific chemical exposures has been the subject of numerous studies, e.g. [60, 61], since this class of composite materials has been long used successfully in the field of mechanical engineering. In the case of epoxy resins, a slight water absorption is observed which leads to swelling of the polymer and damage, especially in the interphase between filament and polymer matrix. In combination with tensile stresses due to service loads, delamination and cracking can occur in the impregnated polymer. Once formed, these micro-structural disturbances are preferred transport paths for chemicals, which can reach filament surfaces largely unhindered and attack the fibre bulk material. The interaction of alkalis and  $\text{OH}^-$ -ions from pore solution of concrete can induce hydrolysis, followed by embrittlement of the impregnation material. The extent to which such damage occurs depends on the material and mechanical properties of the impregnation resin, the degree of cross-linking, the process control during impregnation and thus the matrix content in relation to fibre content.

Few published scientific works are available on the durability of FRP reinforcement elements in concrete. Investigations on reinforcements made of AR glass yarns impregnated with epoxy resins showed a reduction of strength loss up to 50% compared to non-impregnated yarns. The diffusion coefficient of the epoxy resin was identified as the decisive factor for the delayed corrosion of AR glass filaments [65]. The

diffusion coefficient depends to a large extent on the degree of cross-linking of the polymers. The higher the degree of cross-linking, the lower the diffusion coefficient. Therefore, hot-curing epoxy resin has a significantly lower diffusion coefficient than cold-curing epoxy resin or water-based systems. The diffusion coefficient increases disproportionately with rising temperature.

In addition to the diffusion coefficient, the cross-sectional shape of the impregnated yarn has been identified as an important factor. Compact yarn cross-sections with a low ratio of circumference to cross-sectional area show a more favourable durability behaviour than flat cross sections [65]. Reinforcement elements with large, compact cross-sections show lower strength losses as well, since only the rim of FRP element is strongly affected by corrosion. Both phenomena result from longer/unfavourable diffusion paths for harmful media into the core area of the reinforcing element. Finally, for incompletely impregnated AR glass yarns, i.e. with some core filaments unprotected by polymer, a more pronounced loss in mechanical performance over time can be expected in comparison to the fully impregnated yarns.

Carbon reinforcements with impregnation by epoxy resin feature a durability behaviour different from AR glass reinforcement [66]. In long-term durability tests the specimens were subjected to a continuous load of 70% to 97% of the short-term strength and stored in a water bath at 40 °C or 60 °C during loading. No loss of strength could be detected. On the contrary, creep effects of the epoxy resin in the reinforcing element resulted in a more uniform stress/strain state for all filaments in the cross-section and thus resulting in an approximate 7% higher residual strength after completion of the long-term durability tests. The extent of alkaline attack on the epoxy impregnation and its role on the results could not be clarified.

The use of styrene-butadiene (SBR) polymers for impregnation of AR glass reinforcements resulted in a pronounced swelling of the polymer when exposed to moisture. The strength loss of reinforcements with SBR impregnation hardly differs from that of non-impregnated reinforcements [65]. The phenomena can be explained by the low cross-linking of the SBR polymer compared to epoxy impregnation since there is only a slight delay in the diffusion of glass attacking chemicals.



It can be concluded that in FRP with mineral fibres (glass, basalt), three major mechanisms can contribute to the failure of the reinforcement: (a) failure of filaments due to chemical attack, (b) failure of polymer matrix and (c) failure of filament-polymer matrix-interphase. In the case of FRP with carbon fibres, the first mechanism, i.e. corrosive attack on the carbon filaments, is insignificant for most scenarios. The extent to which the individual mechanisms affect the durability of the FRP reinforcement depends on the material as well as on the geometric and structural specifications of the reinforcement.

#### 4.2 Durability of mineral matrix

When cement-based mineral matrices are used, their durability can be assessed in accordance with the procedures established for durability assessment of ordinary concrete. The damage mechanisms due to frost, chemical attack, mechanical attack, etc. are identical. However, due to the often-differing composition of matrices for non-metallic reinforcement (binder content and composition, max. grain size of aggregates), the findings established for normal concrete cannot be directly transferred, specifically with respect to the quantitative characteristics.

When using mineral reinforcement fibres with or without impregnation polymer, concrete should have a pH value as low as possible to limit the loss of strength of the reinforcement. This can be achieved by buffering portlandite (CH) and alkalis with pozzolans, which, however, also results in a lower freeze-thaw resistance of concrete. Furthermore, the use of binders with a low  $\text{Ca}^{2+}/(\text{Na}^{+} + \text{K}^{+})$  ratio is advantageous to limit corrosion on glassy filaments.

Since the corrosion mechanisms presented are based on the transport of ions in aqueous media, a low concrete moisture content is advantageous for a long lifetime of the reinforced concrete composites. In uncracked concretes, this condition can be favoured by specific concrete compositions which result in low matrix porosity or by a modification of the concrete matrix with polymers (use of Polymer Cement Concrete, PCC). After crack formation in the matrix, the permeation properties of bulk concrete are largely irrelevant. The access of water with ions to the reinforcement then takes place mainly via cracks.

For the cracks with a small width, a reduction of the corrosion media transport through the crack is likely to

occur due to self-healing [67]. A prerequisite for effective self-healing of cracks is a sufficient supply of CH, which is transported after dissolution through capillary system to the crack rim and deposited there as carbonate. Furthermore, the crack width is reduced by swelling of the matrix components.

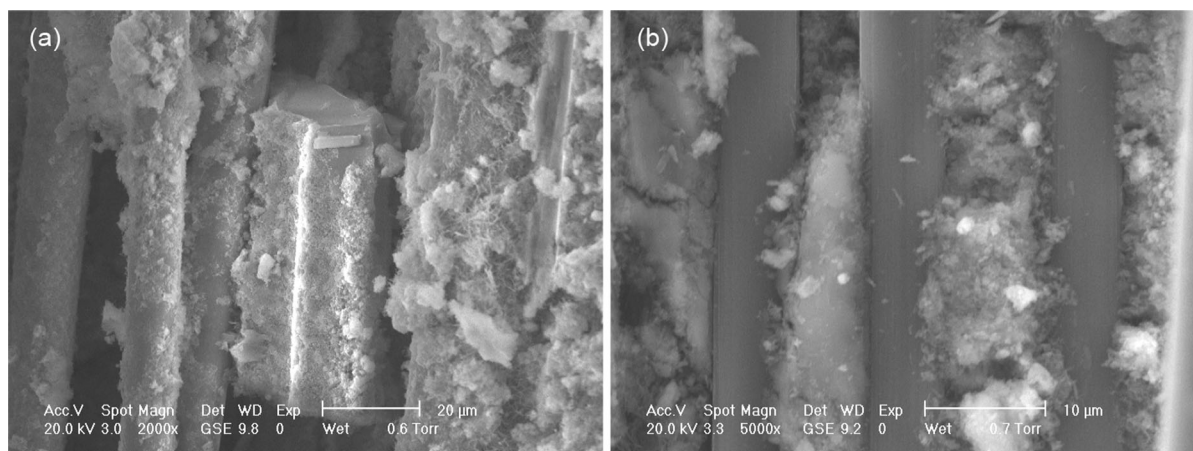
#### 4.3 Durability of the interphase between mineral matrix and reinforcement (FRP)

In addition to the mechanical properties of the fibre, the microstructure of the fibre-matrix interface plays an important role in the performance of the composite material. Cement-based matrices continue to undergo material conversions far beyond the age of 28 days, depending on the ambient conditions. The mechanical properties of the matrix often change only slightly, but the interaction between filaments or filament yarn and matrix can be affected to a far greater extent. In addition to the strength of the composite, such physical changes in the interphase mainly affect the composite's ductility [68].

When fibre reinforcements are used without polymer impregnation, changes in the interphase can have a pronounced effect on the composite behaviour. In this case, transformations and crystalline formations take place directly on the filament surfaces and have a direct effect on their ability to slip in relation to the mineral matrix and other filaments [66, 67]; see Fig. 5. In dense mineral matrices, the crystallisation pressure of hydration products on filament surfaces or the growth of crystal nuclei in surface defects are possible physico-chemical damage mechanisms.

These phenomena have a significantly smaller effect when using reinforcements impregnated by soft polymers, e.g. SBR. Here the contact area for newly formed crystals is limited to the outer surface of the reinforcing element. Direct mechanical (notching) effects by hydration products on filaments surface can hardly occur as they are absorbed by the soft polymer layer. Nevertheless, recrystallisation in the interphase between polymer impregnation and mineral matrix can cause significant changes in the strength and ductility of the composite [55].

In composites with polymer impregnated epoxy-based reinforcements, such changes are hardly present. Here the bond is achieved mainly by positive locking between hard epoxy corrugation and concrete matrix. Any chemical bond between the epoxy-



**Fig. 5** Fibres without polymer impregnation in Portland cement matrix after accelerated ageing of 360 days: **a** large brittle crystals between AR glass lead to low bond performance and failure of fibre at minor stress, **b** encasement of carbon fibres

surfaces and the mineral matrix is hardly present. Accordingly, crystalline new formations or recrystallisation in the interphase with the reinforcement lead only to minor changes in the mechanical behaviour of such composites.

## 5 Dismantling: reuse and recycling

This section gives an overview of the dismantling of non-metallic (FRP) reinforced concrete structures as well as the recycling behaviour and possible reuse strategies. The main focus is on textile reinforced concrete (TRC) elements.

### 5.1 Dismantling and recycling

The process of recycling of composites is influenced by three main factors: materials, composite structure and the crushing process technology [71].

Considering materials, AR glass fibres have proven to be a cost-efficient reinforcement material in use. However, some decline of its mechanical properties over the service life is unavoidable [72], as explained in detail in the previous section. In contrast to glass fibres, carbon fibres retain their mechanical properties in concrete permanently [69] and are, therefore increasingly used as reinforcement material in the construction industry [73]. In addition, basalt fibres are occasionally used as textile reinforcement in concrete.

with fine hydration products leads to permanently strong bonding effect and high mechanical performance of the composite

The influence of the fibre and impregnation material on a possible recovery of the textiles from the concrete matrix could be determined.

Non-impregnated textiles embedded in concrete cannot be recovered from the concrete matrix after crushing in a jaw crusher. This behaviour is independent of the fibre material [74]. Glass textile reinforced concrete falls apart in several pieces with broken glass fibres remaining inside concrete. Concrete with carbon fibre textiles, on the other hand, cannot be crushed in the same way since the carbon fibre rovings do not break completely.

Tests on lab-scale and large-scale TRC specimens with epoxy resin coated carbon fibre textiles showed different behaviour. The epoxy resin made it possible to recover the textiles almost completely from the concrete matrix.

Other coating materials, potassium silicate dissolution and carboxylated styrene butadiene (XSBR), were investigated at the Institut für Textiltechnik of RWTH Aachen University [71, 75]. Textiles coated with XSBR showed concrete adhesions on approx. 40% of the textile surface, while severe damages to the textile structure were visible with the naked eye. Textiles coated with potassium silicate solution could not be recovered because of a tight bond at the contact surface between concrete matrix and the coating.

One aspect regarding the composite structure is the type of the textile reinforcement. Warp-knitted fabrics are usually applied in TRC [76–79]. They consist of

high-strength yarns or fibre bundles oriented in two different directions and fastened by the knitting thread [80]. A second aspect is the trough-thickness-position of the reinforcement layer in the concrete matrix.

It has been found that the yarn cross-section pronouncedly influences the recoverability of reinforcement. The structure of the textiles with a smaller diameter (low yarn titre) is severely damaged during the crushing. Textiles with larger diameters (high titre) remained in a macroscopically intact textile structure after treatment in a jaw crusher. Therefore, the recovered textiles could be re-embedded into fresh concrete. However, the tensile properties of TRC with recovered glass textiles were reduced by up to 25% compared to new textiles [74].

The position of the reinforcement layer in the concrete matrix (in the middle or near the surface) does not influence the recoverability significantly. After the recovery from the crushing process, the textiles gained from near-surface position appear to have less damage, but in the mechanical tests they exhibit a decrease of 20% to 40% of their original strength which is comparable to centrally positioned textiles [71].

A broad range of crushing process technologies has been investigated so far. Mechanical crushing is the conventional crushing technology that focuses on applying mechanical stress to comminute hard and brittle materials, such as concrete. Additionally, due to the specific properties of fibres and textiles, unconventional methods are also under investigation. These include electro-hydraulic and electro-dynamic crushing, which are suitable for the selective separation of composites into brittle and tough-breaking material.

Most investigations on crushing of TRC components for recycling purposes were carried out with jaw crushers [71, 74, 81–83]. This technology is commonly used for the crushing of hard and brittle mineral construction waste by compressive and impact forces. Other units for shredding brittle material are hammer mills and impact mills. Here the material is comminuted by a high-speed rotor, which is equipped with rigid or mobile tools causing shock and impact stresses. All devices lead to three processing products: concrete, fibre/textile fragments and a mixture of concrete and fibre/textile [71, 82]. Comparing the mechanical crushing devices, the best exposure of reinforcement after a single feed can be achieved with the hammer mill: 91% of the total carbon fibre

reinforcement input can be recovered as pure material; see Fig. 6. After jaw crushing, the share of pure carbon fibre is only 0.75% and after impact milling, not more than approximately 13%.

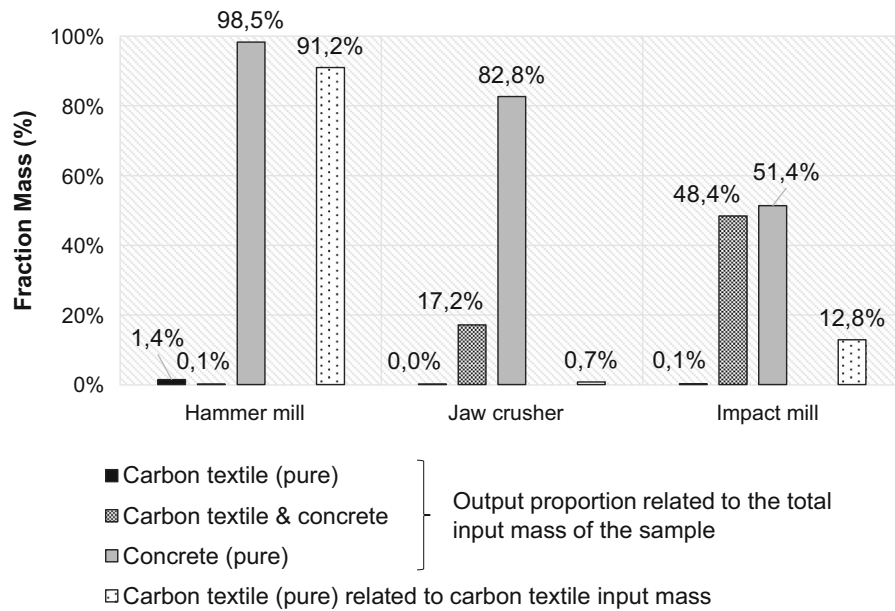
Additionally, the damage to the reinforcement caused by the crushing differs depending on the device. In Fig. 7, recovered SBR-coated carbon fibre reinforcement of TRC specimens is shown as a crushing product of (a) jaw crusher, (b) impact mill and (c) hammer mill. Therefore, in addition to the purity of the recovered products, their condition should be considered. With respect to the reinforcement, three general types of damage can be identified: failure of the roving, failure of the warp yarn and adhesive concrete. In Fig. 7c can be seen that the warp yarn—and therefore the entire textile structure—is completely destroyed by treatment in a hammer mill.

Tests with electrohydraulic- and electrodynamic crushing were performed on a lab scale. Here, the feed material was subjected to wet-mechanical stress in water with voltage-induced shock waves caused by electrodes. By electrodynamic crushing, the concrete matrix can be damaged with just a few pulses in a way that the fabric is exposed easily. Even though the reinforcement cannot be currently completely recovered, the method shows the highest potential for further research, according to [82]. With both technologies, again three output fractions are produced: concrete fractions, carbon fibres and textiles as well as concrete fragments containing carbon fibre. All outputs and the process water show a slight accumulation of carbon fibres.

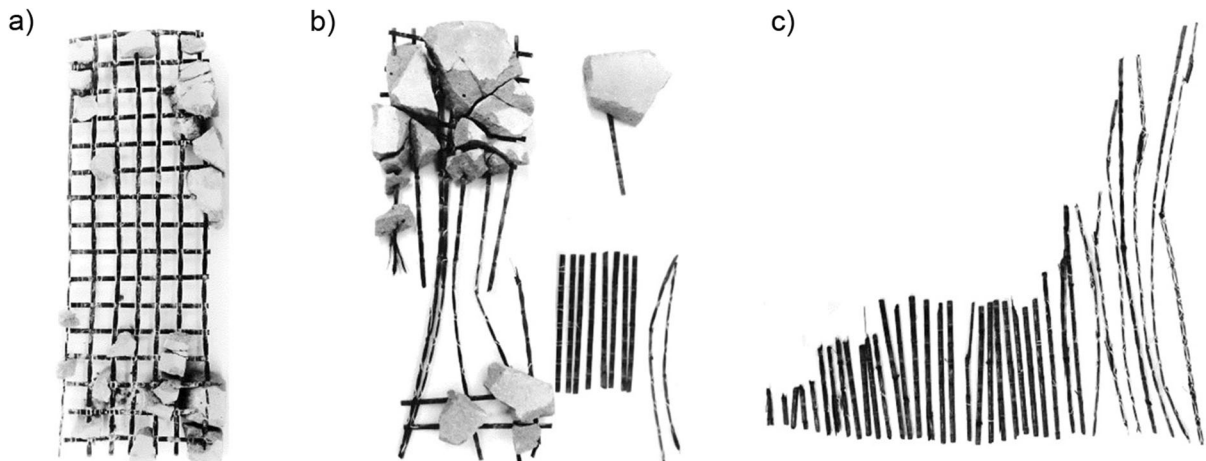
Choosing the sorting technology is the last step to regain the carbon fibre reinforcement for reuse. Research has shown that the sorting technologies used in the construction sector do not necessarily deliver the best separation results.

Conventional separation of mineral demolition material is carried out with screening technologies, e. g. air screening or sieving. There are two major aspects of carbon fibre reinforcement, which lead to a low separation rate using these technologies. The difference in density between carbon fibre reinforcement ( $1.9 \text{ g/cm}^3$ ) and mineral demolition material ( $2.2$  to  $2.5 \text{ g/cm}^3$ ) is not high enough to separate the fibres with air screening machines and the crushing of the demolition material leads to small parts of carbon fibre reinforcement, which orient themselves with the material flow and therefore are not held by sieves.





**Fig. 6** Mass fractions of the output after comminution [71]



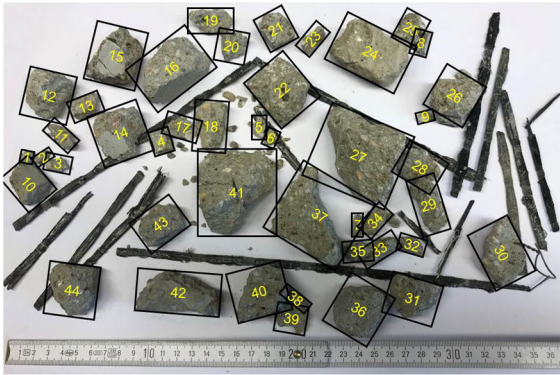
**Fig. 7** Recovered carbon fibre fractions after comminution with **a** the jaw crusher, **b** the impact mill, and **c** the hammer mill [71]

Experiments with sieves have shown separation rates between 5% (large scale experiments) and 20% (laboratory scale) when using sieves and a separation rate of 8 to 10% when using air screening technologies.

Due to the low separation rates resulting from the use of conventional technologies, separation and sorting technologies used in other industries have been investigated. The technologies investigated were fluidised bed sorting, density-based sorting, manual sorting, infrared-based sorting and camera-based

sorting. As for the previous experiments, the investigated technologies showed mixed results. The best separation results were reached with the density-based sorting using sodium polytungstate: a sorting rate of 100%. However, due to the expected volume of the material stream and the high price of a high-density liquid this solution currently does not qualify for a large scale use [84].

The camera-based sorting turned out to be the preferable solution both for technical and economic reasons. The camera-based sorting focuses on the



**Fig. 8** Detection of cubic mineral fraction [83]

difference in geometry of the mineral part of the demolition material (cubical shape) and the carbon fibre reinforcement (pencil-shaped); see Fig. 8. The camera recognises the different shapes in the passing material stream and the carbon fibre fragments are then targeted and blown off. This technology reaches a separation rate of approximately 98% and is already used in waste separation facilities. These boundary conditions are the base for the adaptation of the technology within the construction sector. It is also a chance for new stakeholders to get involved in the material cycle of carbon fibre reinforcement. The result of a camera-based sorting is shown in Fig. 9.

## 5.2 Reuse

Regarding deconstructed TRC elements, the European waste hierarchy recommends recycling according to the “Preparation for Reuse” principle. For a successful implementation of this concept, the manufacturer’s product responsibility needs to be enforced in the construction sector as well, so that used TRC products can be disassembled non-destructively, refurbished if necessary and reinstalled in new construction projects. New business models, such as leasing concepts, would promote this utilisation. Unfortunately, the current legal and political system does not promote the reusability and recyclability of new building products and materials. So, currently reuse of the recycled fractions from crushed TRC is investigated on different levels. In the following the current research on reusing the textile and fibre fraction as well as the concrete fraction will be summarised.

For glass fibre reinforced concrete without polymer impregnation, the state of the art is either landfill

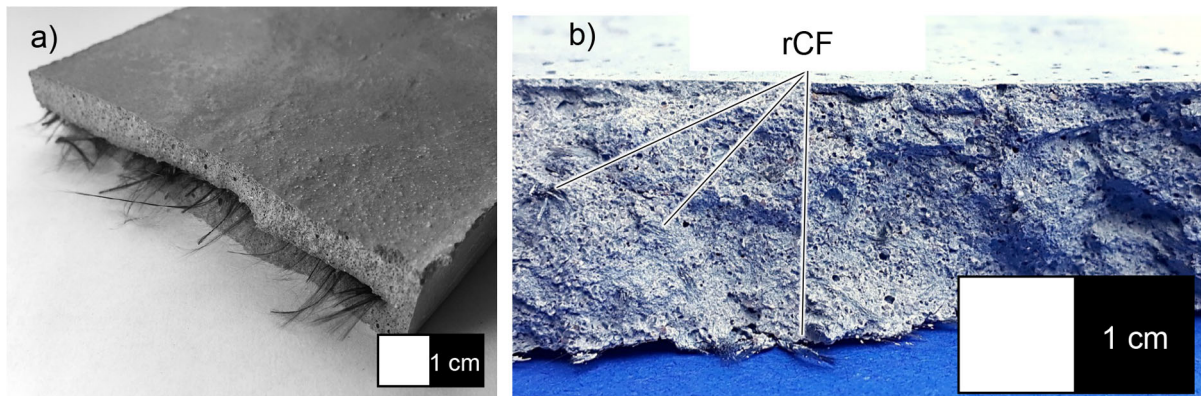


**Fig. 9** Result of camera based sorting [83]

(landfill class 0—low contaminated mineral waste) or its use as filling material in road construction. This is possible due to the purely inorganic materials contained inside. A higher quality recycling by redirecting the recycled aggregates into the original products is aimed for, however, it has not yet been implemented on a large scale.

TRC made of glass or carbon fibre with a polymer impregnation can be categorised according to its origin and has to be treated in different ways. Textile waste can occur during cutting processes in the production of TRC, it is then free from concrete. Methods for the removal of polymer impregnation, e.g. pyrolysis, already exist in an industrial scale. Textile waste is also produced from crushing demolished TRC elements and subsequent separation from concrete. In the following a second use of recovered textile reinforcement is described as (1) an entire secondary reinforcement, (2) a textile reinforcement made of nonwovens or yarns, and (3) a short fibre reinforcement.

To investigate a reuse of secondary textile reinforcement in its original application, reinforcements coated with epoxy resin were extracted from crushed TRC samples after the jaw crusher run [75]. Non-impregnated and SBR-impregnated reinforcements as well as the hammer and impact mill processes are not suitable for a second application as a reinforcement, because the textile or grid-like structure is too damaged to be recovered in textile shape. After jaw crushing, recovered textiles were placed in new TRC specimens. For performing tests, several textiles had to be rejected due to excessive damage, mostly



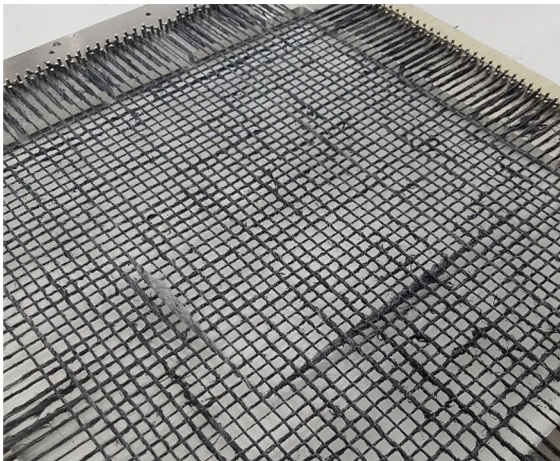
**Fig. 10** **a** Concrete slab with nonwoven reinforcement (rCF and PVA fibres) produced at Institut für Textiltechnik of RWTH Aachen University/ITA Augsburg, and **b** use of recycled carbon fibres in fibre concrete (here: volume content of 2%)

because of a completely destroyed textile structure. Only six of originally ten textile specimens were admissible for the bending tests, which were then performed according to DIN EN 1170-5. Compared to TRC reinforced with new textiles, the flexural strength of the specimens with recycled reinforcement textiles was 20% to 40% lower. The results showed that recovered textiles are not suitable to be processed into TRC, if the same level of performance is to be achieved as with new textiles [68, 72].

In order to use a textile nonwoven reinforcement made of recycled fibres, the post-processing of TRC waste requires the separation of fibres with a length of more than 40 mm [85–87] and a further treatment step to separate fibres from their impregnation. Nonwovens, mostly new AR glass fibres, are currently used in concrete technology for different purposes like to improve the cracking behaviour. Generally, nonwovens are a cost-effective textile product since no step for yarn production is necessary. In comparison to recycled glass fibres, the use of recycled carbon fibres (rCF) is economically more suitable since the new fibre has higher material costs. Against this background, nonwovens made of rCF and polyvinyl alcohol (PVA) fibres were developed whereby the PVA fibres serve to improve the processability in the nonwoven production process and the bonding of the nonwoven to concrete. In contrast to carbon nonwovens for the use in plastic matrices, a low density and a low weight per unit area of the nonwoven is required for percolation with concrete. A first material prototype can be seen in Fig. 10a. The material properties are currently being optimised in further research [88].

To produce yarns from recycled carbon fibres, the same post-processing of TRC waste as for the above-mentioned nonwoven reinforcement is necessary. As a prerequisite for the textile processing the carbon fibres have to be mixed with thermoplastic fibres with a mixing ratio of 50% of each fraction. The mixture ensures, that the carbon fibres do not break during the textile processing. Subsequently, the fibre mixture is combed to reach a uniform alignment of the fibres. Afterwards, the strand of aligned fibres is compressed and multiple layers are stacked on top of each other to increase the amount of fibres per cross-section. The compact strand can be handled as a normal textile fibre strand and can be woven into yarns for further use, e. g. into new reinforcement structures. The described process is part of ongoing research and will be improved to gain a maximum quality of carbon fibres. Current points of concern are the brittleness of carbon fibres after pyrolysis and the mechanical stress on the fibre during the textile processing, both being possible reasons for fibres to break and therefore to compromise the mechanical properties of the recycled product (Fig. 11).

Mixing short fibre into concrete leads to so-called fibre reinforced concrete (FRC). FRC is the material of choice if improvements in tensile strength, ductility and impact resistance are desired. The addition of fibres during the mixing process of concrete or mortar leads to a random distribution of short fibres and thus to isotropic properties of the material. Carbon fibres for short fibre reinforcement of concrete and mortar have been investigated since the 1980s, but have not yet been able to establish themselves in the concrete



**Fig. 11** Carbon fibre reinforcement made of recycled carbon fibre yarn (TU Dresden, Institute of Textile Machinery and High Performance Material Technology)

fibre market for economic reasons [89–92]. Contrary, rCF for FRC, see Fig. 10b, show promising results. Typical volume contents of up to 2 vol.% and lengths of 5 mm to 40 mm for FRC have been investigated [88, 93, 94]. The results show that rCF as a short fibre reinforcement for concrete is more efficient and economically competitive compared to conventional fibre reinforcement, i.e. short AR glass or steel fibres. rCF is resource-saving since 40% to 80% less fibre mass is required to achieve the same mechanical properties as in a conventional FRC. Additionally, rCF is resistant to chemical damage and moisture and thus offers long-term durability in challenging environments [88, 95, 96].

The reuse of the mineral fraction after sorting can be handled as per the regulations of the applicable norms and standards. There are two major differences between conventional mineral demolition material and concrete reinforced with carbon. Usually, high strength concrete is used in carbon fibre reinforced construction parts. On the one hand, good mechanical properties can be beneficial for the production of recycled concrete, on the other hand, the concrete might not be part of the standards and norms applicable for the production of recycled concrete. Before further usage of the mineral fraction, the properties have to be tested and the material should not be mixed with other mineral fractions. The second special circumstance is a minimal residue of carbon fibres within the mineral fraction. The minimal

amount of the remaining carbon fibre material, i.e. approximately 2% of the 2 vol.% used in the construction element, does not have any measurable effect on the performance of recycled concrete and is usually covered by the norms and standards as an organic residue in recycling material. However, such recycling material can be a bit irritating because of its fibrous appearance.

## 6 Summary

Non-metallic reinforcement in the form of glass fibre textiles has been the most widely used form for the past three decades. In the meantime, the non-metallic reinforcement range has been extended to basalt and carbon fibre-based reinforcement systems, systems based on synthetic fibres such as PE, PA (e.g. Aramid) or PP, and extruded rod-like systems (FRP bars) made of various fibre types. The increasing application of such non-metallic reinforcement systems during recent years is well described in the literature, often accompanied by statements on the sustainable nature of these systems without giving further proof in the form of an LCA. The present paper is a contribution which should facilitate qualified and quantified statements (LCA) from different perspectives (impact categories) of comparable systems (functional units). For this reason, the principles of LCAs are briefly explained and a review of the relevant but scarce literature is given with a focus on non-metallic reinforcement systems. Subsequently, a data set of different impact categories for non-metallic reinforcement systems is compiled which, to this extent, is unique so far. This data set distinguishes the individual components of non-metallic reinforcement systems, i.e. fibre and matrix, and, in addition, states as reference different impact categories for reinforcement steels of various origins. This finally allows for the generation of LCAs of different reinforcement solutions in civil engineering structures according to different impact categories. In doing so, it becomes clear that:

1. Accurate LCI data is still very limited. LCI data, such as GWP for reinforcement steel, can vary to a large extent depending on, e.g., the origin of the product. The use of generic EPDs is only recommended if no primary LCI data is available.

2. It is very important to define the impact categories during a Life Cycle Impact Assessment (LCIA) since environmental decision-making processes might change depending on the considered impact category; cf. different ranking of reinforcing material depending on environmental impact class chosen in Fig. 3.
3. The comparison of the environmental impact of different materials must be at least normalized according to their mechanical performance per unit volume or, preferably, for a functional unit, which is in the best case the entire structure with comparable specifications (regarding size, use, loads, etc.).

Very often, LCAs are limited to the production phases A1–A3 (cradle-to-gate) only. However, the real benefits of alternative and supposedly more sustainable materials such as non-metallic reinforcement become clear during the life cycle as a result of increased service life and decrease in repair and maintenance demand (B1–B3). Yet, the real impact on the aforementioned benefits is hardly quantifiable because it is influenced by a large number of factors and their interactions. To give the reader at least a guideline for a selection of a reinforcement system this paper explains the main degradation processes for the introduced non-metallic reinforcement systems.

Finally, the end-of-life stages (C1–C4 and D) should also be considered in a decision-making process as the most sustainable solution (cradle-to-grave) is not truly sustainable if demolition, disposal or recycling poses a big burden to the environment or society. For this reason, this new research field is comprehensively reviewed as well. The review shows the possibilities to positively influence an LCA by the choice of a specific non-metallic reinforcement system on the one hand. On the other hand, it also reveals the very high degree of complexity in this matter. The type of non-metallic reinforcement, its composite structure and the selected crushing technology can notably influence the result of the LCA to the better or to the worse as well. The titre of the textile forming yarns, for example, determines the degree of fibre or even textile fraction that can be recovered after crushing. In the same way, crushing technology has a paramount impact on the degree of reusable reinforcement after demolition and recycling. It has been shown that conventional technologies established in construction industry such as jaw crushing are no preferable solutions. Preferred systems

such as hammer mills are, however established technologies in other industries.

Eventually, sorting processes have been reviewed that would follow the crushing process. Here in particular camera-based sorting systems such as those used in communal waste separation facilities show the best results regarding a thorough separation of reinforcement and concrete matrix. The last section of the presented paper focuses on the reuse of the separated non-metallic reinforcement components. Here, crushing technology again is decisive whether the recovered reinforcement, textiles in this case, can be used again. In contrast to a pure separation-based perspective, hammer and impact mill processes are not preferred, and jaw crushing delivers best results. However, recovered textiles suffer from a serious strength loss. Another approach might be the production of fibre strands and textiles from recycled fibre fractions, as has been demonstrated for carbon fibres.

The above-described findings emphasize that a preferably comprehensive description of the structure, including material choice, origin and configuration, e.g. in a BIM program, is a prerequisite for the selection of an adequate demolition and recycling path.

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#### Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

- Krausmann F, Lauk C, Haas W, Wiedenhofer D (2018) From resource extraction to outflows of wastes and emissions: the socioeconomic metabolism of the global economy, 1900–2015. *Glob Environ Chang* 52:131–140. <https://doi.org/10.1016/j.gloenvcha.2018.07.003>
- Andrew RM (2018) Global CO<sub>2</sub> emissions from cement production 1928–2017. *Earth Syst Sci Data* 10:195–217. <https://doi.org/10.5281/zenodo.831455>
- OECD (2019) Global material resources outlook to 2060: economic drivers and environmental consequences. OECD
- Kromoser B, Preinstorfer P, Kollegger J (2019) Building lightweight structures with carbon-fiber-reinforced polymer-reinforced ultra-high-performance concrete: Research approach, construction materials, and conceptual design of three building components. *Struct Concr* 20:730–744. <https://doi.org/10.1002/suco.201700225>
- Preinstorfer P, Kromoser B, Kollegger J (2019) Flexural behaviour of filigree slab elements made of carbon reinforced UHPC. *Constr Build Mater* 199:416–423. <https://doi.org/10.1016/j.conbuildmat.2018.12.027>
- Stoiber N, Hammerl M, Kromoser B (2021) Cradle-to-gate life cycle assessment of CFRP reinforcement for concrete structures: calculation basis and exemplary application. *J Clean Prod* 280:124300. <https://doi.org/10.1016/j.jclepro.2020.124300>
- Bakis ChE (2009) Life cycle analysis issues in the use of FRP composites in civil infrastructure. In: Proceedings of US-Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials. Sapporo, Japan
- Russell-Smith SV, Lepech MD (2009) Life cycle assessment of FRP seismic retrofitting. In: Proceedings of US-Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials
- Mara V, Haghani R, Sagemo A, et al (2013) Comparative study of different bridge concepts based on life-cycle cost analyses and life-cycle assessment. In: Proceedings of the Asia-Pacific Conference on FRP in Structures (APFIS 2013). Melbourne, Australia
- Zhang C (2014) 23—Life cycle assessment (LCA) of fibre reinforced polymer (FRP) composites in civil applications. In: Pacheco-Torgal F, Cabeza LF, Labrincha J, de Magalhães A (eds) Eco-efficient construction and building materials. Woodhead Publishing, pp 565–591
- Inman M, Thorhallsson ER, Azrague K (2017) A mechanical and environmental assessment and comparison of basalt fibre reinforced polymer (BFRP) rebar and steel rebar in concrete beams. *Energy Procedia* 111:31–40. <https://doi.org/10.1016/j.egypro.2017.03.005>
- Cadenazzi T, Dotelli G, Rossini M, et al (2019) Life-cycle cost and life-cycle assessment analysis at the design stage of a fiber-reinforced polymer-reinforced concrete bridge in Florida. *Adv Civ Eng Mater* 8:ACEM20180113. <https://doi.org/10.1520/ACEM20180113>
- van Loon RRL, Pujadas-Gispert E, Moonen SPG, Blok R (2019) Environmental optimization of precast concrete beams using fibre reinforced polymers. *Sustainability* 11:2174. <https://doi.org/10.3390/su11072174>
- Ibrahim M, Ebead U, Al-Ansari M (2020) Life cycle assessment for fiber-reinforced polymer (FRP) Composites used in concrete beams: a state-of-the-art review. Qatar University Press
- Estes A, Frangopol D (2005) Life cycle evaluation and condition assessment of structures. In: Chen WF, Lui EM (eds) *Structural Engineering Handbook*, 2nd Edition, CRC Press, New York
- Prinçaud M, Aymonier C, Loppinet-Serani A et al (2014) Environmental feasibility of the recycling of carbon fibers from CRFRPs by solvolysis using supercritical water. *ACS Sustain Chem Eng* 2:1498–1502. <https://doi.org/10.1021/sc500174m>
- Pang B, Yang P, Wang Y et al (2015) Life cycle environmental impact assessment of a bridge with different strengthening schemes. *Int J Life Cycle Assess* 20:1300–1311. <https://doi.org/10.1007/s11367-015-0936-1>
- Maxineasa SG, Taranu N, Bejan L et al (2015) Environmental impact of carbon fibre-reinforced polymer flexural strengthening solutions of reinforced concrete beams. *Int J Life Cycle Assess* 20:1343–1358. <https://doi.org/10.1007/s11367-015-0940-5>
- Portal NW, Lundgren K, Wallbaum H, Malaga K (2015) Sustainable potential of textile-reinforced concrete. *J Mater Civ Eng* 27:04014207. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001160](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001160)
- Palacios-Munoz B, Gracia-Villa L, Zabalza-Bribián I, López-Mesa B (2018) Simplified structural design and LCA of reinforced concrete beams strengthening techniques. *Eng Struct* 174:418–432. <https://doi.org/10.1016/j.engstruct.2018.07.070>
- Maxineasa SG, Taranu N (2018) 24—Life cycle analysis of strengthening concrete beams with FRP. In: Pacheco-Torgal F, Melchers RE, Shi X et al (eds) Eco-efficient repair and rehabilitation of concrete infrastructures. Woodhead Publishing, pp 673–721
- Nunes AO, Viana LR, Guineheuc P-M et al (2018) Life cycle assessment of a steam thermolysis process to recover carbon fibers from carbon fiber-reinforced polymer waste. *Int J Life Cycle Assess* 23:1825–1838. <https://doi.org/10.1007/s11367-017-1416-6>
- Garg N (2019) Shrivastava S (2019) Environmental and economic comparison of FRP reinforcements and steel reinforcements in concrete beams based on design strength parameter. in: UKIERI Concrete Congress, Jalandhar, India
- Pillain B, Loubet P, Pestalozzi F, et al (2019) 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* 154:104607. <https://doi.org/10.1016/j.supflu.2019.104607>



25. Cadenazzi T, Dotelli G, Rossini M et al (2020) Cost and environmental analyses of reinforcement alternatives for a concrete bridge. *Struct Infrastruct Eng* 16:787–802. <https://doi.org/10.1080/15732479.2019.1662066>
26. Chen C, Yang Y, Zhou Y, et al (2020) Comparative analysis of natural fiber reinforced polymer and carbon fiber reinforced polymer in strengthening of reinforced concrete beams. *J Clean Prod* 263:121572. <https://doi.org/10.1016/j.jclepro.2020.121572>
27. Demertzi M, Silvestre JD, Durão V (2020) Life cycle assessment of the production of composite sandwich panels for structural floor's rehabilitation. *Eng Struct* 221:111060. <https://doi.org/10.1016/j.engstruct.2020.111060>
28. Scope C, Guenther E, Schütz J et al (2020) 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 Design* 2:143–158. <https://doi.org/10.1002/cend.202000024>
29. Akbar A, Liew KM (2020) Assessing recycling potential of carbon fiber reinforced plastic waste in production of eco-efficient cement-based materials. *J Clean Prod* 274:123001. <https://doi.org/10.1016/j.jclepro.2020.123001>
30. Dong S, Li C, Xian G (2021) Environmental impacts of glass- and carbon-fiber-reinforced polymer bar-reinforced seawater and sea sand concrete beams used in marine environments: an LCA case study. *Polymers (Basel)* 13:E154. <https://doi.org/10.3390/polym13010154>
31. Xiong C, Li Q, Lan T, et al (2021) Sustainable use of recycled carbon fiber reinforced polymer and crumb rubber in concrete: mechanical properties and ecological evaluation. *J Clean Prod* 279:123624. <https://doi.org/10.1016/j.jclepro.2020.123624>
32. Stoiber N, Hammerl M, Kromoser B (2021) Environmental assessment of non-metallic reinforcement for concrete structures as an alternative to steel reinforcement. In: Proceedings of the ICCS 2021. Prague, Czech Republic
33. Niewels J (2009) Zum Tragverhalten von Betonbauteilen mit Faserverbundkunststoff-Bewehrung. Dissertation, RWTH Aachen
34. Reichenbach S, Preinstorfer P, Hammerl M, Kromoser B (2021) A review on embedded fibre-reinforced polymer reinforcement in structural concrete in Europe. *Constr Build Mater* 307:124946. <https://doi.org/10.1016/j.conbuildmat.2021.124946>
35. Ehlig D, Schladitz F, Frenzel M, Curbach M (2012) Textilbeton—Ausgeführte Projekte im Überblick. *Beton- und Stahlbetonbau* 107:777–785. <https://doi.org/10.1002/best.201200034>
36. Scholzen A, Chudoba R, Hegger J (2015) Thin-walled shell structures made of textile-reinforced concrete. *Struct Concr* 16:106–114. <https://doi.org/10.1002/suco.201300071>
37. Helbig T, Unterer K, Kulas C et al (2016) Fuß- und Radwegbrücke aus Carbonbeton in Albstadt-Ebingen: Die weltweit erste ausschließlich carbonfaserbewehrte Betonbrücke. *Beton- und Stahlbetonbau* 111:676–685. <https://doi.org/10.1002/best.201600058>
38. Rempel S, Will N, Hegger J, Beul P (2015) Filigrane Bauwerke aus Textilbeton. *Beton- und Stahlbetonbau* 110:83–93. <https://doi.org/10.1002/best.201400111>
39. Kromoser B, Huber P, Preinstorfer P (2018) Analyzation of the shear load bearing behaviour of thin walled CFRP reinforced UHPC structures. In: Proceedings of the 5th International fib Congress 2018. Melbourne, Australia
40. Suppanz F, Kromoser B (2020) Verbundverhalten subtraktiv bearbeiteter CFK-Stäbe in UHPC. *Beton- und Stahlbetonbau* 115:504–513. <https://doi.org/10.1002/best.201900088>
41. Bielak J, Spelter A, Will N, Claßen M (2018) Verankerungsverhalten textiler Bewehrungen in dünnen Betonbauteilen. *Beton- und Stahlbetonbau* 113:515–524. <https://doi.org/10.1002/best.201800013>
42. Preinstorfer P, Kromoser B, Kollegger J (2018) Einflussparameter auf die Spaltrissbildung in Textilbeton. *Beton- und Stahlbetonbau* 113:877–885. <https://doi.org/10.1002/best.201800071>
43. Preinstorfer P, Kollegger J (2020) New insights into the splitting failure of textile-reinforced concrete. *Compos Struct* 243:112203. <https://doi.org/10.1016/j.compstruct.2020.112203>
44. ift Rosenheim GmbH (2022) Umweltproduktdeklaration (EPD) Bewehrungs- und Befestigungssysteme solidian GRID und solidian REBAR. solidian GmbH
45. Hammerl M, Kromoser B (2020) Prestressing of carbon fiber reinforced concrete. In: Proceedings of HiPerMat 2020: 5th international symposium on ultra-high performance concrete and high performance construction materials, pp 17–18. <https://doi.org/10.17170/kobra-202002271026>
46. Hammerl M, Kromoser B (2021) The influence of pretensioning on the load-bearing behaviour of concrete beams reinforced with carbon fibre reinforced polymers. *Compos Struct* 273:114265. <https://doi.org/10.1016/j.compstruct.2021.114265>
47. PwC—Sustainable Performance and Strategy (2023) Life cycle assessment of CFGF—Continuous Filament Glass Fibre Products
48. Kromoser B, Reichenbach S, Stoiber N, et al (2022) Potentiale von nichtmetallischer Bewehrung im Infrastruktur-Betonbau NIMETBEW (VIF2019)—final Report. [https://projekte.ffg.at/anhang/62790e46a3083\\_NIMETBEW\\_Ergebnisbericht.pdf](https://projekte.ffg.at/anhang/62790e46a3083_NIMETBEW_Ergebnisbericht.pdf)
49. European Composites Industry Association EuCIA (2023) ECO IMPACT CALCULATOR for composites. <https://ecocalculator.euCIA.eu>. Accessed 29 Mar 2023
50. Hohmann A (2018) Life cycle assessment of manufacturing processes for CFRP structures to identify optimization potentials—systematic methodology for estimating the environmental impact of manufacturing process chains. Technical University of Munich
51. Azrague K, Inman MR, Alnæs (2016) Life Cycle Assessment as a tool for resource optimisation of continuous basalt fibre production in Iceland. In: Proceedings of the Conference for Life Cycle Assessment and Other Assessment Tools for Waste Management and Resource Optimization
52. Stoiber N, Hammerl M, Kromoser B (2021) Cradle-to-gate life cycle assessment of CFRP reinforcement for concrete structures: calculation basis and exemplary application. *J Clean Prod* 280:124300. <https://doi.org/10.1016/j.jclepro.2020.124300>



53. PwC (2015) EPDLA Life Cycle Assessment Summary Report
54. Kromoser B (2020) Ressourceneffizientes Bauen mit Betonfertigteilen: Material-Struktur-Herstellung. In: Bergmeister K, Fingerloos F, Wörner J-D (eds) Betonkalender 2021: Fertigteile; Integrale Bauwerke. Ernst & Sohn GmbH & Co. KG
55. Scheffler C, Förster T, Mäder E et al (2009) Aging of alkali-resistant glass and basalt fibers in alkaline solutions: evaluation of the failure stress by Weibull distribution function. *J Non-Cryst Solids* 355:2588–2595. <https://doi.org/10.1016/j.jnoncrysol.2009.09.018>
56. Förster T, Scheffler C, Mäder E et al (2014) Dissolution behaviour of model basalt fibres studied by surface analysis methods. *Appl Surf Sci* 322:78–84. <https://doi.org/10.1016/j.apsusc.2014.10.058>
57. Förster T (2016) Einfluss der chemischen Zusammensetzung und der Oberflächenmodifizierung auf die Eigenschaften von Basaltfasern. Dissertation, Technical University Dresden
58. Wetjen D (2016) Wechselwirkung von Carbonfasern, Schlichte und Epoxidbasierter Polymerer Matrix in Carbonfaserverstärkten Kunststoffen. Dissertation, University Augsburg
59. Pourbaix M (1974) Atlas of electrochemical equilibria in aqueous solutions. NACE International, Houston, Texas, USA.
60. Micelli F, Nanni A (2004) Durability of FRP rods for concrete structures. *Constr Build Mater* 18:491–503. <https://doi.org/10.1016/j.conbuildmat.2004.04.012>
61. Scheffler C, Gao SL, Plonka R et al (2009) Interphase modification of alkali-resistant glass fibres and carbon fibres for textile reinforced concrete II: water adsorption and composite interphases. *Compos Sci Technol* 69:905–912. <https://doi.org/10.1016/j.compscitech.2008.12.020>
62. Kruppke I, Butler M, Schneider K et al (2019) Carbon fibre reinforced concrete: dependency of bond strength on Tg of Yarn impregnating polymer. *Mater Sci Appl* 10:328–348. <https://doi.org/10.4236/msa.2019.104025>
63. Bank LC, Gentry TR, Barkatt A (1995) Accelerated test methods to determine the long-term behavior of FRP composite structures: environmental effects. *J Reinf Plast Compos* 14:559–587. <https://doi.org/10.1177/073168449501400602>
64. Ray BC (2006) Temperature effect during humid ageing on interfaces of glass and carbon fibers reinforced epoxy composites. *J Colloid Interface Sci* 298:111–117. <https://doi.org/10.1016/j.jcis.2005.12.023>
65. Büttner TF (2015) Zur Dauerhaftigkeit polymergetränkter AR-Glas Bewehrungen in Textilbeton. Dissertation, RWTH Aachen
66. Spelter A, Bergmann S, Bielak J, Hegger J (2019) Long-term durability of carbon-reinforced concrete: an overview and experimental investigations. *Appl Sci* 9:1651. <https://doi.org/10.3390/app9081651>
67. Mechtcherine V, Lieboldt M (2011) Permeation of water and gases through cracked textile reinforced concrete. *Cement Concr Compos* 33:725–734. <https://doi.org/10.1016/j.cemconcomp.2011.04.001>
68. Butler M, Mechtcherine V, Hempel S (2010) Durability of textile reinforced concrete made with AR glass fibre: effect of the matrix composition. *Mater Struct* 43:1351–1368. <https://doi.org/10.1617/s11527-010-9586-8>
69. Butler M, Hempel S, Mechtcherine V (2009) Zeitliche Entwicklung des Verbundes von AR-Glas- und Kohlenstofffaser-Multifilamentgarnen in zementgebundenen Matrices. In: Colloquium on Textile Reinforced Structures (CTRS4). Dresden, Germany
70. Cohen Z, Peled A (2010) Controlled telescopic reinforcement system of fabric–cement composites—durability concerns. *Cem Concr Res* 40:1495–1506. <https://doi.org/10.1016/j.cemconres.2010.06.003>
71. Kimm M, Gerstein N, Schmitz P et al (2018) On the separation and recycling behaviour of textile reinforced concrete: an experimental study. *Mater Struct* 51:122. <https://doi.org/10.1617/s11527-018-1249-1>
72. Orłowsky J, Raupach M (2006) Modelling the loss in strength of AR-glass fibres in textile-reinforced concrete. *Mater Struct* 39:635–643. <https://doi.org/10.1617/s11527-006-9100-5>
73. Assmann U, Offermann P (2015) Nutzung der abZ “Verfahren zur Verstärkung von Stahlbeton mit TUDALIT® (Textilbewehrter Beton).” *Beton- und Stahlbetonbau* 110:109–109. <https://doi.org/10.1002/best.201400108>
74. Koch A, Rübmann DJ, Kersch C (2015) Recycling von Carbonbeton: Vorstellung der aktuellen Vorarbeiten. In: TUDALIT e.V. (Ed.): 7. Anwendertagung Textilbeton. TUDALIT e.V., Dresden, Germany
75. Kimm MK, Gerstein N, Vollpracht A et al (2017) Characterization of separability of carbon textile reinforced concrete for increased material sustainability. in: Proceedings of the 71st RILEM Annual Week & ICACMS 2017, Chennai, India. RILEM Publications S.A.R.L
76. Cohen Z, Pasder A, Roye Y, Gries T (2006) Effects of warp knitted fabrics made from multifilament in cement-based composites. ICTRC’2006—1st International RILEM Conference on Textile Reinforced Concrete. RILEM Publications SARL, Aachen, pp 23–32
77. Koeckritz U, Cherif C, Weiland S, Curbach M (2010). In-situ polymer coating of open grid warp knitted fabrics for textile reinforced concrete application. *J Indus Tex* 40:157–169. <https://doi.org/10.1177/1528083709102938>
78. Quadflieg T, Stolyarov O, Gries T (2016) Influence of the fabric construction parameters and roving type on the tensile property retention of high-performance rovings in warp-knitted reinforced fabrics and cement-based composites. *J Indus Tex* 47:453–471. <https://doi.org/10.1177/1528083716652831>
79. Younes A, Seidel A, Rittner S et al (2015) Innovative textile Bewehrungen für hochbelastbare Betonbauteile. *Beton- und Stahlbetonbau* 110:16–21. <https://doi.org/10.1002/best.201400101>
80. Padaki N, Alagirusamy R, Sugun B (2006). Knitted preforms for composite applications. *J Indus Tex* 35:295–321. <https://doi.org/10.1177/1528083706060784>
81. Bienkowski N, Hillemann L, Thorsten S et al (2017) Bearbeitung von Carbonbeton—eine bauverfahrenstechnische und medizinische Betrachtung. *Bauingenieur* 2017:110–117
82. Jäckel H-G (2018) CF-bewehrte Betone—ein künftiges Entsorgungsproblem?: Ausgewählte Ergebnisse zur Recyclingfähigkeit. Stuttgart, Germany



83. Kortmann J, Kopf F, Hillemann L, Jehle P (2018) Recycling von Carbonbeton. Aufbereitung im großtechnischen Maßstab gelungen. *Bauingenieur* 38–44
84. Kortmann J (2020) Verfahrenstechnische Untersuchungen zur Recyclingfähigkeit von Carbonbeton. In: Jehle O, Jehle P (eds) *Baubetriebswesen und Bauverfahrenstechnik*. Springer, Verlag
85. Rübmann D, Lütke C, Löhner M, et al (2014) Innovative recycling processes for carbon fibre based materials to provide innovative and cost competitive composites. In: Eren R (ed) *14th AUTEX World Textile Conference 2014*, Bursa, Turkey
86. Rübmann D, Zobel S, Gries T et al (2013) Comminution and characterization of carbon staple fibers produced from rejects. *Chem Fibers Int* 63:98–101
87. Wolf K, Merkel A (2014) Abschlussbericht—Spinnverfahren für recycelte Carbonfasern—phase 1. Edited by Gebrüder Otto Baumwollfeinzwirner GmbH & Co. KG
88. Kimm M, Pico D, Gries T (2020) Investigation of surface modification and volume content of glass and carbon fibres from fibre reinforced polymer waste for reinforcing concrete. *J Hazard Mater* 390:121797. <https://doi.org/10.1016/j.jhazmat.2019.121797>
89. Akihama S, Suenaga T, Banno T (1984) The behaviour of carbon fibre reinforced cement composites in direct tension. *Int J Cem Compos Lightweight Concrete* 6:159–168. [https://doi.org/10.1016/0262-5075\(84\)90004-6](https://doi.org/10.1016/0262-5075(84)90004-6)
90. Chen P-W, Chung DDL (1993) Concrete reinforced with up to 0.2 vol% of short carbon fibres. *Composites* 24:33–52. [https://doi.org/10.1016/0010-4361\(93\)90261-6](https://doi.org/10.1016/0010-4361(93)90261-6)
91. Hambach M (2017) *Hochfeste multifunktionale Verbundwerkstoffe auf Basis von Portlandzement und Kohlenstoffkurzfasern*. Dissertation, University Augsburg
92. Toutanji HA, El-Korchi T, Katz RN (1994) Strength and reliability of carbon-fiber-reinforced cement composites. *Cement Concr Compos* 16:15–21. [https://doi.org/10.1016/0958-9465\(94\)90026-4](https://doi.org/10.1016/0958-9465(94)90026-4)
93. Mastali M, Dalvand A, Sattarifard A (2017) The impact resistance and mechanical properties of the reinforced self-compacting concrete incorporating recycled CFRP fiber with different lengths and dosages. *Compos B Eng* 112:74–92. <https://doi.org/10.1016/j.compositesb.2016.12.029>
94. Mastali M, Dalvand A (2016) The impact resistance and mechanical properties of self-compacting concrete reinforced with recycled CFRP pieces. *Compos B Eng* 92:360–376. <https://doi.org/10.1016/j.compositesb.2016.01.046>
95. Kimm M (2019) Recycling von Carbonbeton—Wie kann eine hochwertige Wiederverwendung gelingen? In: *Proceedings der 11. Carbon - und Textilbetontage*. C3 Carbon Concrete Composite e.V.; TUDALIT e.V., Dresden, Germany
96. Kimm MK, Gries T (2019) High performance and durable fiber concrete made of recycled carbon fibers. In: Baričević A, Jelčić Rukavina M, Damjanović D, Guadagnini M (eds) *International conference on sustainable materials, systems and structures (SMSS 2019): durability, monitoring and repair of structures*. Rovinj, Croatia

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