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ENVIRONMENTAL ASSESSMENT OF NON-METALLIC REINFORCEMENT FOR CONCRETE STRUCTURES AS AN ALTERNATIVE TO STEEL REINFORCEMENT

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Abstract.

The concrete industry accounts for a significant amount of CO_2 emissions worldwide. One approach to counter this issue includes material reduction of structural components via the use of non-metallic reinforcement, such as carbon, glass and basalt fibre reinforced polymers. On the one hand, non-metallic reinforcement. However, as its environmental impact has not been sufficiently investigated yet, a Life Cycle Assessment of the production phase is presented within this paper. In a first step, the environmental impact of the sole various reinforcement components and types is compared to each other per mass, per tensile or rather yield strength as well as density unit, at which an environmental disadvantage of especially carbon-fibre reinforced polymers is apparent in most cases. In a further step, a focus is put on applying the environmental data of carbon-fibre reinforced polymers to a pedestrian bridge, which is finally compared to a conventionally reinforced concrete bridge and a steel bridge with similar boundary conditions. The latter results indicate that an adequate application of carbon-fibre reinforcement in structural components has the potential to lead to designs of less environmental impact in comparison to conventionally reinforced pendants.

Keywords: Concrete structures, environmental impact, FRP reinforcement, life cycle assessment, non-metallic reinforcement.

1. Introduction: 'Concrete footprint'

According to [1], in 2018 the construction industry was responsible for approximately 10% of CO_2 emissions worldwide. On a global level, the report further identifies concrete as most widely used building material type. What is more, it is predicted by [2] that the building material concrete will account for around 12% of worldwide greenhouse gas emissions in 2060. Besides emissions regarding the production phase and respective required fuels, concrete is characterised by so-called process emissions due to its intrinsic chemical reduction from calcium carbonate to calcium oxide, which represent around two thirds of total emissions [3]. These numbers outline the urgency as well as the potential of the concrete industry in pushing attempts to decrease its emission-intensity forward.

Several options exist to counter the above outlined issue, at which three major approaches, according to [4], are briefly listed: Reducing the amount of cement via an optimization of the concrete mixture, a reduction of concrete material used via a structural optimization of the design as well as the use of high-strength materials such as ultra-high performance concrete (UHPC) and fibre-reinforced polymers (FRP) made out of basalt, glass or carbon fibres. The latter approach is pursued within this paper, at which the environmental performance is subject of investigation.

Firstly, the method and materials are outlined. Secondly, the investigated reinforcement types are compared with each other, solely on material level. Here, several matrix as well as fibre types are analysed. Subsequently, the application of the environmental data of carbon fibre-reinforced polymers to pedestrian bridges as conducted in [5] is presented.

2. Methodology: Life Cycle Assessment

According to EN ISO 14050, Life Cycle Assessment (LCA) is described as an assessment of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. LCA is divided into several phases, including Life Cycle Inventory (LCI) analysis, where the inputs and outputs of a product system are determined, as well as Life Impact Assessment Analysis (LCIA), where the environmental impacts of a product system are evaluated and assessed. Several characterisation models exist regarding the latter step of an LCA, at which CML-IA from the University Leiden is mentioned within this context [6].

The underlying standardisation of conducting an LCA comprises EN ISO 14040 (fundamentals) and EN ISO 14044 (instructions). EN ISO 14025 outlines the use of Life Cycle Assessment to establish an Envi-

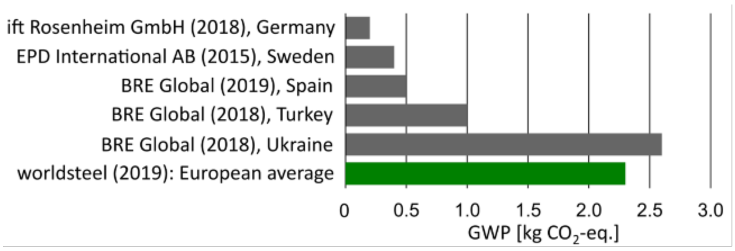

Figure 1. Comparison of GWP values extracted from EPDs with the European average of [7].

ronmental Product Declaration (EPD). The national standard ÖNORM EN 15804 has to be highlighted in this context, which regulates the development of EPDs for the product category of construction products. Life cycle phases of a product system range from product, construction process to the end of life stage. The product stage is compulsory to be covered when developing an EPD, at which this stage is divided into three categories: Raw material supply (A1), transport (A2) and manufacturing (A3). This type of LCA is described as cradle-to-gate. Commonly, a cradle-to-gate LCA represents the most adequate type, as the inputs and outputs are often characterised by satisfying data completeness and quality. Other life cycle stages, such as the construction process stage, are accompanied by comparatively more underlying assumptions. At best, all life cycle stages are covered within an EPD. Due to limited data availability, the production stage of the considered construction products is assessed within this paper. Furthermore, several impact indicators are selected to be evaluated, such as the Global Warming Potential (GWP) in kg CO_2-eq., the Acidification Potential (AP) in kg SO_2-eq. as well as the Abiotic Deletion Potential of fossil fuels (ADPf) in MJ. Commonly, due to public popularity, the GWP is paid the most attention to. In order to establish a wider picture of the environmental impact of the considered products, further impact indicators should be assessed.

Consulted sources within this paper include EPDs and Life Cycle Inventory data. Details about the respective sources as well as the chosen declared or rather functional units are outlined in the sections below. It is crucial to note that irregularities go hand in hand with the comparison of environmental data from varying sources. For example, the LCIA phase of the Life Cycle Assessment can be based on varying characterisation models. The authors aimed at maintaining maximum transparency within the process to enable traceability and reproducibility.

2.1. Excursion: Data bias

To briefly outline the phenomenon of data bias and raise awareness regarding data quality within Life Cycle Assessment, the example of steel reinforcement is consulted. Extracted GWP values of steel reinforcement (cradle-to-gate LCA, declared unit: 1 kg) as done by [5] are illustrated in Figure 1. The first five, grey bars represent extracted GWP values from European EPDs, at which the last, green bar outlines the European average of steel production in 2019 provided by [7]. For further detailed information on data sources of the EPDs, the reader is directly referred to [5]. Given the GWP values extracted from the EPDs in Figure 1, one would assume to have an average value of around 1.0 kg CO_2-eq., nevertheless, the European average is higher. When analysing the manufacturing methods of the various EPDs it becomes apparent that, except for Ukraine, all EPDs are built up on electric arc furnace. Nevertheless, [8] shows otherwise, at which not electric arc furnace but basic oxygen steelmaking represents the major manufacturing method of steel products in Europe. The average of the given data extracted from the EPDs is therefore not representative for the Global Warming Potential of steel reinforcement in Europe.

3. Results on material level: Comparison of reinforcement components and types

Figure 2 and Figure 3 show the normalized results of the GWP of various fibre and matrix types. GWP values for carbon fibres are extracted from [9], for glass fibres from [10], for basalt fibres from [11], for styrene butadiene rubber and acrylate from [12], for polyester resin, vinylester resin and epoxy resin from [13] as well as from [14]. Impact indicators, like the GWP, were directly extracted from these sources. Only the last source, [14], represents LCI data, which was extracted and subjected to self-evaluation according to the specifications of ÖNORM EN 15804:2020. In all cases, the production stage (cradle-to-gate) was considered.

Regarding Figure 3 it is apparent that carbon fibres are characterised by the highest Global Warming Potential in comparison to glass and basalt fibres. As reason the energy-intense production process up to 3,000řC is mentioned. The differences between the various matrix materials in Figure 2 are not that significant, nevertheless, a row in dependence of the GWP is possible. The normalized GWP values of carbon fibre-reinforced polymers (CFRP), glass fibre-reinforced polymers (GFRP) and basalt fibre-reinforced polymers (BFRP) are illustrated in Figure 4, at which epoxy resin was chosen as matrix material. The results are presented in a normalized

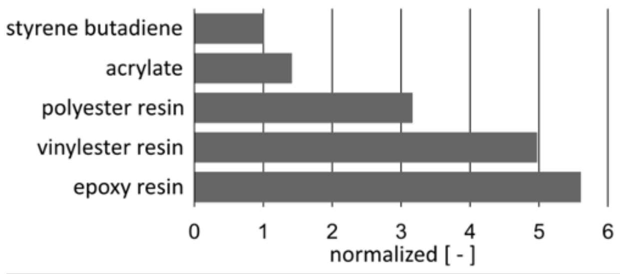

Figure 2. Comparison of the GWP of different matrix materials (normalized values).

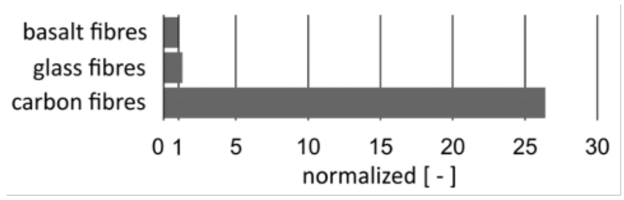

Figure 3. Comparison of the GWP of different fibre types (normalized values).

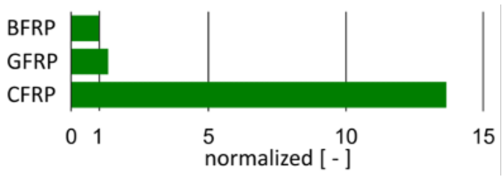

Figure 4. Comparison of the GWP of different FRPs (normalized values).

manner to enhance readability. The respective components of the FRPs were combined according to an analysis of data sheets, at which the respective fibre share ranges from 75 to 90% and the matrix material share ranges from 10 to 25%. The GWP of carbon fibres of 26.4 kg CO_2-eq. per kg was extracted from [9] and is given as example. Comparing Figure 3 with Figure 4 it can be seen that the trend of carbon being the least favourable material choice in case of environmental impact continues, nevertheless the difference between the varying fibre types becomes smaller. In this context, the study of [15] is mentioned, who conducted a cradle-to-grave LCA for conventional steel- and textile-reinforced (glass, carbon and basalt) façade elements. Their findings indicate that all textile versions show comparatively less environmental impact. The carbon version showed a comparatively higher impact than the glass or basalt solution amongst most of the investigated impact indicators (GWP, AP and Eutrophication Potential).

3.1. In detail: CFRP reinforcement

The environmental impact of CFRP is further investigated based on evaluations done in [5], at which the analysis is extended to impact indicators such as the Acidification Potential in kg SO_2-eq. (AP) and the Abiotic Depletion Potential of fossil fuels in MJ (ADPf). Furthermore, the environmental impact of CFRP reinforcement is directly compared to the one of conventional steel reinforcement (European average, compare with Figure 1). The results are illustrated in Figure 5 to Figure 7. The properties of a CFRP rebar product from solidian GmbH are consulted [16].

In Figure 5, the results are solely based on masses or rather per declared unit of 1 kg of the product system. This figure shows the environmental advantage of conventional steel reinforcement in comparison to CFRP reinforcement amongst all considered impact indicators.

Figure 6, which is based on masses as well as on the performance of the reinforcement type, still shows environmental benefits of steel reinforcement. Nevertheless, an additional consideration of the performance, more precisely the tensile strength of 2,100 MPa of CFRP reinforcement as well as the yield strength of 550 MPa of steel reinforcement shows results more on favour of CFRP reinforcement than a sole consideration of the masses as illustrated in Figure 5.

Figure 7 shows otherwise, at which an environmental benefit of CFRP reinforcement amongst the impact indicators GWP and ADPf is visible. Here, the performance (tensile and yield strength) as well as the related densities (7,850 kg/m^3 for steel reinforcement, 1,500 kg/m^3 for CFRP reinforcement) were considered. Figure 7 already shows the potential of CFRP reinforcement as an environmentally friendly alternative to steel reinforcement on the material level.

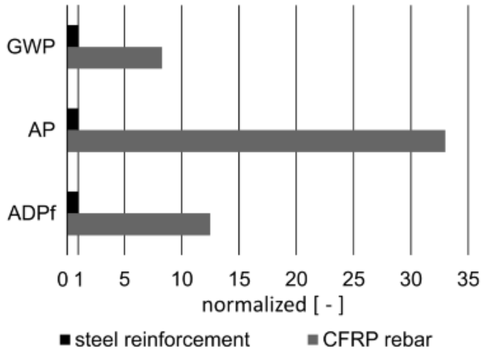

Figure 5. Comparison of steel and CFRP reinforcement per kg product system (normalized values).

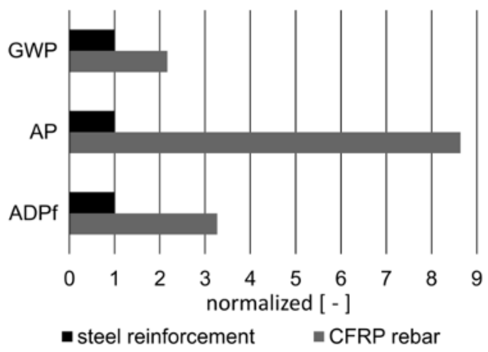

Figure 6. Comparison of steel and CFRP reinforcement per kg product system as well as per MPa tensile respectively yield strength (normalized values).

4. Results on system level: Comparison of pedestrian bridges

The environmental data of CFRP were further applied to pedestrian bridges of varying building types by [5], whose results will be outlined as a subsequent step. The consulted bridges are illustrated in Figure 8. The first bridge is a carbon concrete bridge in Albstadt Ebingen, Germany and was built in 2015 (abbreviated with B1-CCB), which is characterised by a thin CFRP reinforced cross section and a galvanized steel railing. The second bridge is a conventional steel reinforced concrete bridge, built in 2009 in Vienna, Austria (abbreviated with B2-RCB). The last bridge, a mild steel bridge, was built in 1999 in Vienna, Austria (abbreviated with B3-SB). The masses for the quantity survey were extracted from [17] for B1-CCB and provided by the Municipal Department 29 in Vienna Austria in case of B2-RCB and B3-SB. Further details can be found in [5]. The functional unit for the subsequent comparison is a pedestrian bridge with a span length of ~ 15 m, an effective width of ~ 3 m and an imposed load of ~ 5 kN/m^2. The materials of the superstructure were considered.

The results of the environmental assessment of the pedestrian bridge types are illustrated in Figure 9. The impact indicators GWP and ADPf are clearly in favour of the CFRP reinforced concrete bridge due to

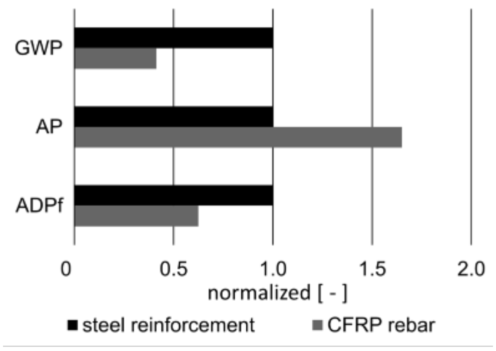

Figure 7. Comparison of steel and CFRP reinforcement per MPa tensile respectively yield strength as well as per density unit (normalized values).

significant savings in material masses when comparing B1-CCB with B2-RCB.

To get a deeper understanding of the allocation of the environmental impacts, the results are furthermore divided per building material and outlined in Figure 10 to Figure 12. The consideration of the GWP as well as of the ADPf shows that the galvanized steel railing of B1-CCB has a significant share in the whole environmental impact. Regarding ADPf, the reinforcement is responsible for the majority of the environmental impact. Regarding AP in Figure 11, it becomes apparent that the CFRP reinforcement is mainly responsible. The environmental data are characterised by high limits of variation, at which [9] gives the consultation of different reaction equations for the combustion of ammonia and hydrocyanic acid during the production process of carbon fibres as reason for these variabilities. This circumstance outlines room for higher data precision regarding the AP in the future. Furthermore, the authors want to indicate, that a more comprehensive consideration of the environmental impact was initially intended, with further impact indicators such as Ozone Depletion Potential (ODP), Eutrophication Potential (EP) and Photochemical Oxidant Creation (POCP) being considered. Unfortunately, the respective environmental data of CFRP were either not available nor valid. Updates in the data availability are constantly checked and re-evaluated by the authors.

5. Conclusion

The intention of this paper was to evaluate, whether fibre-reinforced polymers are a possible environmentally friendly alternative to conventional steel reinforcement in concrete structures or not. In a first step, the varying fibre and matrix material types were solely evaluated per unit weight, at which carbon fibres and CFRP reinforcement showed by far the highest Global Warming Potential. Subsequently, a more detailed environmental assessment of CFRP reinforcement on material level showed that steel reinforcement is more favourable when considering solely the declared unit of 1 kg as well as the declared unit

Figure 8. Pedestrian bridge examples, from top to bottom: B1-CCB (solidian GmbH), B2-RCB and B3-SB (Mathias Hammerl).

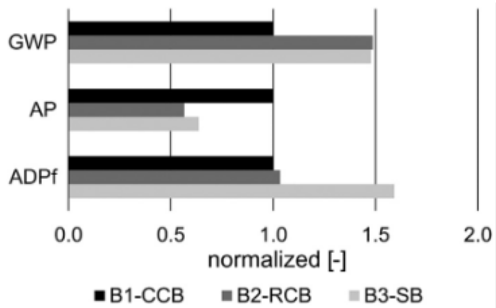

Figure 9. Comparison of impact indicators of various pedestrian bridge types (normalized values), extracted from [5].

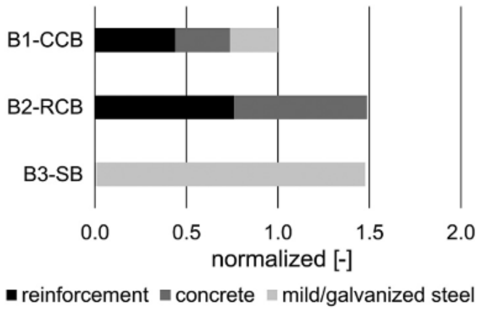

Figure 10. Comparison of the GWP of various pedestrian bridge types (normalized values) divided by the used building materials, extracted from [5].

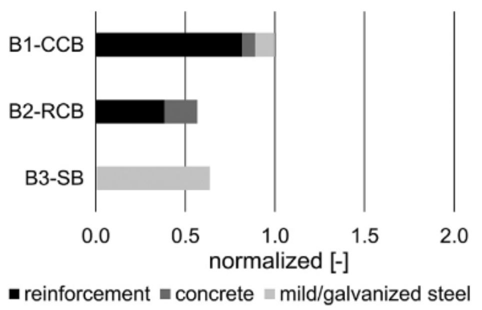

Figure 11. Comparison of the AP of various pedestrian bridge types (normalized values) divided by the used building materials, extracted from [5].

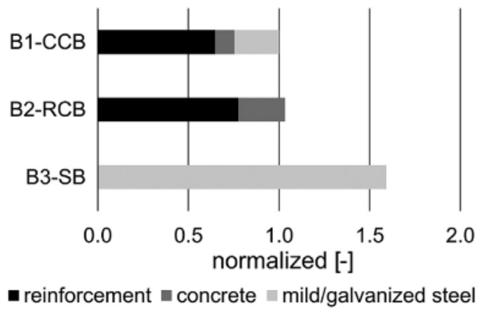

Figure 12. Comparison of the ADPf of various pedestrian bridge types (normalized values) divided by the used building materials, extracted from [5].

in combination with the tensile or rather the yield strength of the respective material. Nevertheless, the consideration of the reinforcements' performance as well as the density of the material showed a lesser environmental impact of CFRP reinforcement in comparison with conventional steel reinforcement. In a second step, an assessment and comparison of the superstructure of a carbon concrete, a reinforced concrete and a mild steel pedestrian bridge outlined the environmental benefits of the carbon concrete bridge type. The potential of CFRP as an environmentally friendly alternative to steel reinforcement in the case of pedestrian bridges could be shown. It has to be mentioned that overall conclusions of this application example to other structures are not acceptable: An individual profound analysis is always necessary. Furthermore, only the production stage of the reinforcement components and pedestrian bridge materials was considered. A more holistic consideration of further life cycle stages with an extension to other structural components is highly recommended as an optimal continuation of this study.

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References

[1] International Energy Agency and the United Nations Environment Programme. 2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector, 2018. https://wedocs.unep.org/handle/20.500.11822/27140.

[2] OECD. Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences (Paris: OECD Publishing), 2019. https://www.oecd.org/environment/waste/highlights-global-material-resources-outlook-to-2060.pdf.

[3] G. Mauschitz.Emissionen aus Anlagen der Österreichischen Zementindustrie, 2018.

[4] B. Kromoser, P. Preinstorfer, J. Kollegger. Building lightweight structures with carbon-fiber-reinforced polymer-reinforced ultra-high-performance concrete: Research approach, construction materials, and conceptual design of three building components. *Structural Concrete* **20**(2):730-44, 2018. https://doi.org/10.1002/suco.201700225.

[5] N. Stoiber, M. Hammerl, B. Kromoser. Cradle-to-gate life cycle assessment of CFRP reinforcement for concrete structures: Calculation basis and exemplary application. *Journal of Cleaner Production* **280**, 2021. https://doi.org/10.1016/j.jclepro.2020.124300.

[6] CML. Department of Industrial Ecology, CML-IA Characterisation Factors, 2016. https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors.

[7] World Steel Association. Life Cycle Inventory (LCI) Request Form, 2019. https://www.worldsteel.org/steel-by-topic/life-cycle-thinking/lca-lciform.html.

[8] World Steel Association. World Steel In Figures 2019, Brussels, 2019.

[9] A. Hohmann. Life cycle assessment of manufacturing processes for CFRP structures to identify optimization potentials - Systematic methodology for estimating the environmental impact of manufacturing process chains, Dissertation: Technical University of Munich, 2018.

[10] Pwc. Life Cycle Assessment of CFGF - Continuous Filament Glass Fibre Products, 2016. https://www.glassfibreeurope.eu/wp-content/uploads/2016/11/LCA-report-CFGF-products_20161031_PwC.pdf.

[11] K. Azrague, M.R. Inman, L-I. Alnaes L-I, et al. Life Cycle Assessment as a tool for resource optimisation of continuous basalt fibre production in Iceland, 2016. https://dc.engconfintl.org/cgi/viewcontent.cgi?article=1009&context=lca_waste.

[12] PwC. EPDLA Life Cycle Inventory of Polymer Dispersions, 2015. https://specialty-chemicals.eu/wp-content/uploads/2017/07/4_EPDLA-Life-Cycle-Assessment-LCA-Summary-Report.pdf.

[13] EuCIA. Eco Impact Calculator for composites, 2021. https://ecocalculator.eucia.eu/Account/Login?ReturnUrl=%2F.

[14] PlasticsEurope. Eco-Profiles, 2005. https://www.plasticseurope.org/de/resources.

[15] L. Laiblová, J. Pešta, A. Kumar, et al. Environmental Impact of Textile Reinforced Concrete Facades Compared to Conventional Solutions - LCA Case Study. *Materials* **12**(19), 2019. https://doi.org/10.3390/ma12193194.

[16] Solidian. Technical data sheet solidian REBAR 04-CCE, 2020. https://solidian.com/wp-content/uploads/solidian-REBAR-TDS.pdf.

[17] T. Helbig, K. Unterer, C. Kulas, et al. Fuß- und Radwegbrücke aus Carbonbeton in Albstadt-Ebingen. *Beton- und Stahlbetonbau* **111**(10):676-85, 2016. https://doi.org/10.1002/best.201600058.