SUSTAINABILITY OF REINFORCEMENT ALTERNATIVES FOR CONCRETE

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ABSTRACT
The building construction industry is in need of sustainable materials and solutions. A novel building material, such as Textile Reinforced Concrete (TRC), could be used to meet this demand. TRC is a combination of fine-grained concrete and multi-axial textile fabrics, which has been fundamentally researched over the past decade. It was discovered that TRC can be utilized to build slender, lightweight, modular and freeform structures while eliminating the risk of corrosion. TRC-based research has explored various facets of this composite material, such as its structural functionality, production, applicability and design. One key aspect that is still missing, however, is a comprehensive review of the sustainable potential of this material in terms of its reduced use of resources and long-term performance.

This article provides a quantitative evaluation of the sustainable potential and prospective development of TRC particularly reinforced by alkali-resistant (AR) glass, carbon or basalt fibres. A Life Cycle Assessment (LCA) was performed according to a cradle-to-gate perspective, wherein conventional steel reinforced concrete and TRC were compared.

Based on the outcome of this evaluation, concrete was found to be the dominating variable, such that its demand makes up 70-95% of the total energy demand for a reinforced concrete element. A decrease in concrete can thus have a substantial impact on the total energy consumption of a reinforced concrete element. The allowable decrease of concrete in TRC compensates for an increase in textile reinforcement and associated increase in energy consumption, particularly in the case of carbon and basalt textile fibres. On the whole, basalt textile fibres were observed to have the least cumulative energy demand while both basalt and carbon had the least environmental impact. Such comprehensive evaluations can help conceptualize ecologically sustainable building solutions for implementation in the construction industry.

Key words: Textile Reinforced Concrete (TRC), reinforced concrete, Life Cycle Assessment (LCA), façade elements, novel materials.

INTRODUCTION

Based on the current trends and regulations towards zero energy and/or zero carbon buildings, the importance of the environmental performance of construction materials becomes even more indispensable in the near future. EU's 20-20-20 goal [1] and the Energy Performance of Buildings Directive (EPDB) [2] are current examples of adopted goals and legislations mandating that all new buildings need to be zero energy buildings by 2020 within the European Union. Buildings are a

necessity for society but are also one of the greatest energy consumers, thus underlining the need for energy-optimized technologies and constructions. Traditional solutions need an added sustainable element since they primarily focus on cost, performance and quality objectives. Enhancing the ecological sustainability of building materials is beneficial not only in terms of cost and energy savings [3], but also help reduce maintenance and frequency of raw material extraction, as well as increasing the service life of a building.

A recent innovative attempt to improve the sustainability of reinforced concrete is the development of Textile Reinforced Concrete (TRC) encompassing a fine-grained concrete matrix reinforced by multi-axial non-corrosive textile fabrics. This relatively new composite material has been extensively researched at collaborative research centres 532 and 528 at RWTH Aachen University and Dresden University of Technology [4] over the past decade. It was discovered that TRC can be utilized to build slender, lightweight, modular and freeform structures and eliminate the risk of corrosion. The completion of a pedestrian bridge fabricated solely of TRC [5] and the development of thin self-supporting TRC sandwich elements [6] are examples of the possible realizations. Additionally, it was also proven to be an adequate strengthening material for existing reinforced concrete structures in a variety of applications [7, 8].

Vast amounts of building materials exist and are continuing to be developed, but the methods by which their level of sustainability is evaluated remain vague and there is a need for greater transparency. In other words, the categorization of building materials leading to energy-optimized technologies and constructions is not described in the goals and legislations. A method that could be used to expose the environmental impacts of building materials is Life Cycle Assessment (LCA). Environmental standards or recognized certification systems, such as Building Research Establishment Environmental Assessment Method (BREEAM) [9], Leadership in Energy and Environmental Design (LEED) [10] or the German Sustainable Building Council (DGNB) [11], attempt to address the life-cycle impact of construction materials. BREEAM's Green Guide to Specification and the DGNB System's certification process analyse building materials according to their life-cycle impacts; whereas LEED simply emphasize the use of recyclable materials and material reuse. The harmonization of standards for construction materials has been recently directed by requirement no. 7 of EU's Construction Products Regulation [12], which further commends the need for analysis of the sustainable potential of building materials. These discussed facts justify the need for a comprehensive analysis of the sustainable potential of TRC in comparison to conventional building materials, which is explored using a case study: analysis of the environmental impacts of four different reinforced materials, including three types of TRC and conventional steel reinforced concrete.


TRC FAÇADE ELEMENTS
TRC façade elements have recently been developed and applied in a multitude of projects over the past decade. TRC is said to be a sustainable application as it includes non-corrosive reinforcement which grants the fabrication of thin, light-weight and modular façade elements. A brief introduction of the novel building material TRC, as well as an overview of the accomplished projects related to the sustainable application of TRC façade elements are discussed in the following section.

Textile reinforced concrete (TRC)
TRC is a composite material fabricated of a fine-grained concrete matrix reinforced by bi- or multi-axial 2D and 3D textile fabrics. In a simple bi-axial case, the mesh comprises two groups of textile fibre yarns (threads), warp (0°) and weft (90°), interwoven perpendicularly to each other. Yarns are

composed of multiple single fibres of continuous length, also designed as filaments; grouping of continuous fibres is primarily done to obtain the desired thickness of yarn [13]. The main components of TRC are illustrated in Figure 1.
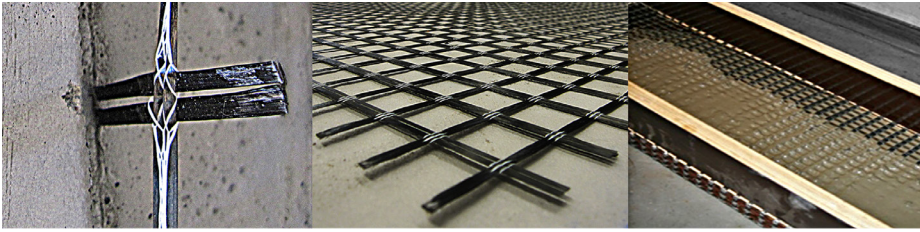
Figure 1 – Components of textile reinforced concrete: yarn, woven mesh and composite form with matrix of fine-grained concrete.

Fibre materials which have generally been used and explored in TRC include, but are not limited to: alkali-resistant glass (AR-glass), carbon, basalt, aramid, polyvinyl-alcohol (PVA) with polyvinyl chloride (PVC) coating and hybrid variants. The choice of fibre material can be based on various factors such as materials properties, corrosion and temperature resistance, bond quality, demand/production cost and even environmental impact. In terms of mechanical behaviour, tensile strength, breaking elongation and modulus of elasticity superior to those related to the cementitious matrix is essential. The reinforcement ratio and placement of the textile reinforcement will also have a great impact on the composite behaviour of a TRC member [14]. Furthermore, the cementitious matrix in TRC differs from that typically used in conventional steel reinforced concrete. Fine-grained concrete also defined as mortar is prescribed for TRC, where the maximum aggregate size is < 2 mm. Highly flowable concrete is needed to adequately penetrate the textile reinforcement mesh structure in order to provide sufficient bond and load transfer.

A sustainable application
The deterioration of concrete structures exposed to humid and saline environments is typically caused by corrosion of steel reinforcement [15]. The protective design cover mandated by *EC2* for steel reinforced concrete structures ranges from 30-75 mm [16], which can significantly be reduced when using non-corrosive textile reinforcements [14]. For instance, it was found by Tomoscheit, Gries [17] that approximately 85 % less concrete is needed for TRC applications using carbon or AR-glass textiles. Furthermore, by conserving energy-demanding materials, such as concrete of Portland cement, the environmental impact of concrete structures can be reduced [14, 18]. Additionally, in the case of lightweight and thin TRC facades, the need for complex anchorage systems is eliminated [14], the environmental impact resulting from transportation from *gate-to-use* is reduced [15, 17], as well, the liveable area within a building can be increased. Within the EU-funded LIFE project entitled INSUSHELL, the application of a self-supporting façade element made of thermally insulated TRC was discovered to save not only high energy and CO_2 in the production phase, but also during the construction phase [6].

The thickness of commonly used precast concrete elements with steel reinforcement is determined based on the application, minimum concrete cover and fire resistance requirements. The use of metallic connectors are also typically incorporated in the design of these elements [19]. The inclusion of non-corrosive reinforcement, in the form of multi-directional textile fabrics, can permit a reduction of panel thickness which, in turn, yields light-weight and slender concrete façade elements. Accordingly, TRC has been recently applied in new construction in the form of lightweight and thin self-supporting sandwich elements as well as large-sized ventilated façade elements [6, 14, 20]. For instance, textile-reinforced cladding panels, that is to say curtain wall

panels were developed for the extension of the Institute of Structural Concrete, RWTH Aachen University, shown in Figure 2.

Figure 2 – Curtain wall construction at Structural Concrete Institute, RWTH Aachen University.

The panels shown in Figure 2 were designed at the Collaborative Research Centre 532, Aachen and produced by Hering. Coated AR-glass fibre mesh was used as reinforcement which was applied in two layers near the surface (≈ 3 mm cover) [14]. This type of panel is designed for wind load and ensures no cracking under service loads.

CASE STUDY: ALTERNATIVE REINFORCEMENT MATERIALS

To capture the sustainable potential of the novel building material TRC, a Life Cycle Assessment (LCA), in accordance with ISO standards ISO 14040:2006 [21] and ISO 14044:2006 [22], was performed wherein conventional steel reinforced concrete and TRC were compared. Common fibre materials used in TRC namely, alkali-resistant glass, carbon and basalt, were evaluated. This assessment has been done according to a cradle-to-gate perspective, so to say extraction and production processes, in order to observe the environmental effects of reducing the concrete cover in TRC structures, as well as those involved in the production of different reinforcement materials. However, the presented study is not considering the material's use and end-of-life stage which would include e.g. maintenance, demolition and waste management according to a cradle-to-cradle approach. To execute the analysis, SimaPro (Version 7.3.3) [23] was used and a functional unit of 1 m^2 of reinforced concrete was assumed throughout the study.

Reference specimen
To ensure an adequate comparison, the one-way flexural capacity of a conventionally steel reinforced concrete section of 1 x 1 x 0.08 m is selected as an arbitrary reference for this study. It is important to mention that the selection of a reinforced concrete section in fact requires the consideration of various mechanical and material properties, but for the sake of simplicity, this analysis solely takes into account the flexural capacity. The one-way flexural capacity of this reference section is calculated assuming that the inner lever arm is 90 % of the effective cross-sectional depth. The TRC alternatives are designed with regards to thickness and quantity of textile reinforcement layers to meet the flexural capacity of the reference section (see Figure 3). Further details regarding the applied methodology are described in [24].

Moreover, it was of interest to further enhance the so-called *Reference* specimens initially chosen for the analysis. The enhancement was accomplished by modifying the concrete and reinforcement

quantities until reaching an optimum solution in terms of energy demand and environmental impact. The minimum thickness limit was defined as 30 mm corresponding to a realistic thickness for a façade panel, and the optimal reinforcement amount remained constant or decreased for all sections. Accordingly, the flexural capacity of the sections decreased to a range that expectedly falls within an acceptable limit for the given application. All TRC options met or exceeded the flexural capacity of the steel reinforced concrete reference section. Table 1 summarizes the differing geometric parameters obtained for the so-called *Reference* and *Optimal* alternatives.
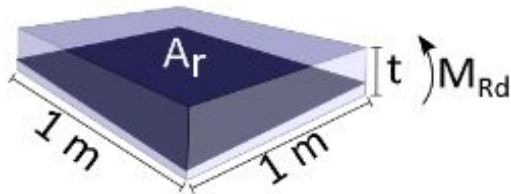

Figure 3 – Reference specimen analysed.

Table 1. Geometric parameters and flexural capacity of Reference and Optimal sections.

Alternatives	Dimensions	Reference			Optimal		
		Thickness t (mm)	Reinfor-cement Layers	Flexural capacity M_{Rd} (kN·m)	Thickness t (mm)	Reinfor-cement Layers	Flexural capacity M_{Rd} (kN·m)
Steel rebar	10ø6 s100	80	1	7.6	30	1	1.9
Glass fibre	2400 tex s8	60	2	8.0	30	2	2.3
Carbon fibre	1600 tex s8	50	2	7.5	30	1	1.9
Basalt fibre	2400 tex s8	50	3	8.6	30	2	3.0

*tex: fineness of yarn (g/1000 m)

The cradle-to-gate data used in this study listed in Table 2 were taken from the readily available databases in SimaPro, namely ecoinvent version 2.2 [25] and the European Reference Life Cycle Database 3.0 (ELCD) [26]. It should be noted that data most adequately representing the desired modelled processes were selected for this study and specific data were not available for each material. Also, due to the fact that the cement component of concrete is known to have the greatest environmental impact [18], concrete was represented simply by an appropriate cement material in the analysis: Portland calcareous cement CEM II for steel reinforced concrete and Portland cement Z 52.5 for TRC.

Table 2. Summary of data used in LCA study.

Material	Equivalent Material	Database
Concrete	*Steel* Portland calcareous cement, at plant	ecoinvent v2.2
	TRC Portland cement, strength class Z 52.5, at plant	
Steel reinforcement	Steel rebar, blast furnace and electric arc furnace route, production mix, at plant	ecoinvent v2.2
Glass fibre	Glass wool, fleece, production mix, at plant, density between 10 to 100 kg/m³	ELCD database 3.0
Carbon fibre	Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives	ELCD database 3.0
Basalt fibre	Rock wool, fleece, production mix, at plant, density between 30 and 180 kg/m³	ELCD database 3.0

Analysis & results

The LCA results are presented in this section commencing by the total cumulative energy demand for each alternative, followed by the corresponding environmental performance based on selected impact methods. The Cumulative Energy Demand (CED) method was used to compute the total cumulative energy demand. This method includes non-renewable energy resources, i.e. fossil and nuclear, as well as renewable energy resources, i.e. biomass, wind, solar, geothermal and water [27]. The total cumulative energy demand, calculated as the summation of the energy resources, can provide a preliminary overview of the demand trend existing between the *Reference* reinforced concrete options (refer to Figure 4).
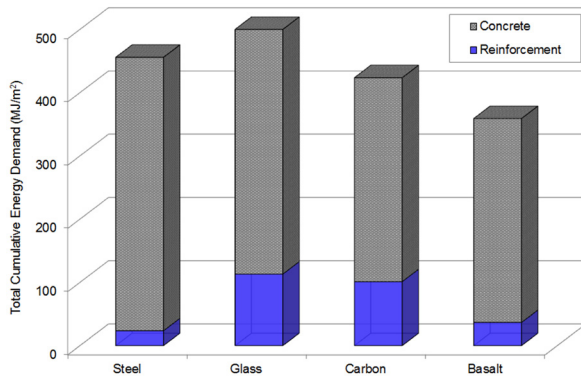

Figure 4 – Total cumulative energy demand of Reference specimens; comparison between concrete and reinforcement (functional unit of 1 m^2).

The main observation that can be drawn from Figure 4 is that concrete is a dominating variable in this equation, such that its demand makes up 70-95 % of the total cumulative energy demand of the reinforced concrete section. Furthermore, basalt fibre reinforced concrete followed by carbon present lower total demands in comparison to the conventional steel reference solution. From these results, it can be concluded that a decrease in concrete, particularly referring to TRC, can have a substantial impact on the total energy consumption of a reinforced concrete element. It is also interesting to mention that the allowable decrease of concrete in TRC compensates for an increase in textile reinforcement and associated increase in energy consumption, particularly in the case of carbon and basalt fibres.

Moving on to the comparison between the total cumulative energy demands of *Reference* specimens to that of *Optimal* ones (see Figure 5), a varying trend is observed for these specimens, such that the dissimilarities between the TRC alternatives and the steel reference are significantly reduced. For instance, concerning the *Reference* values, the difference between glass (10 %), carbon (-7 %) and basalt (-21 %) with respect to steel are in general decreased for the *Optimal* values, with the exception of glass (12 %). Also, the order of the *Optimal* alternatives is altered in terms of lowest to highest energy demand, such that steel yields merely 2 % lower energy demand than carbon.

The environmental impact of the *Reference* and *Optimal* alternatives was evaluated using various impact methodologies: IMPACT 2002+, IPCC 2007 and CML 2000 [28]. IMPACT 2002+ combines 14 midpoint categories to four damage categories. Results are expressed in *points (Pt)* which are equivalent to an average impact in a specific category per person per year. IPCC 2007 is a method from the International Panel on Climate Change providing climate change factors over 20, 100 and 500 years. This method characterizes the direct global warming potential of air emissions in *kg CO$_2$ eq*. Lastly, the CML 2001 methodology assesses the impact according to baseline indicators such as Ozone layer depletion (ODP), human toxicity and Global warming (GWP100). The resulting impact is presented as a normalized score based on the World in 1990 [27].
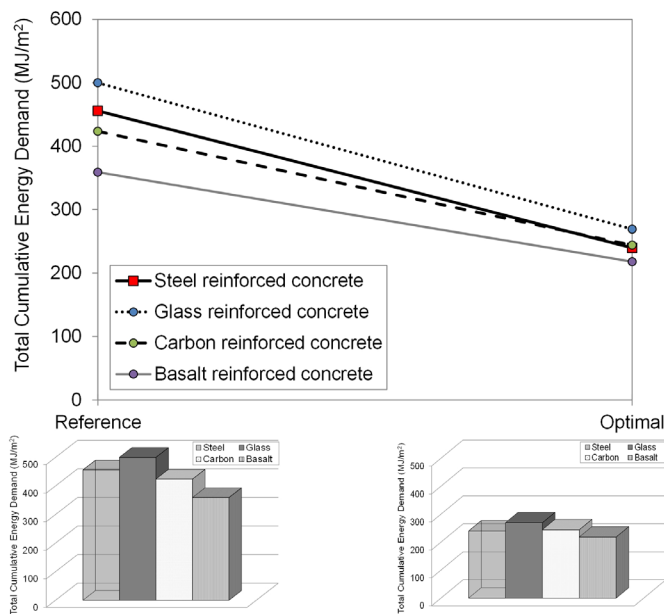
Figure 5 – Total cumulative energy demand; comparison between Reference and Optimal solutions (functional unit of 1 m²).
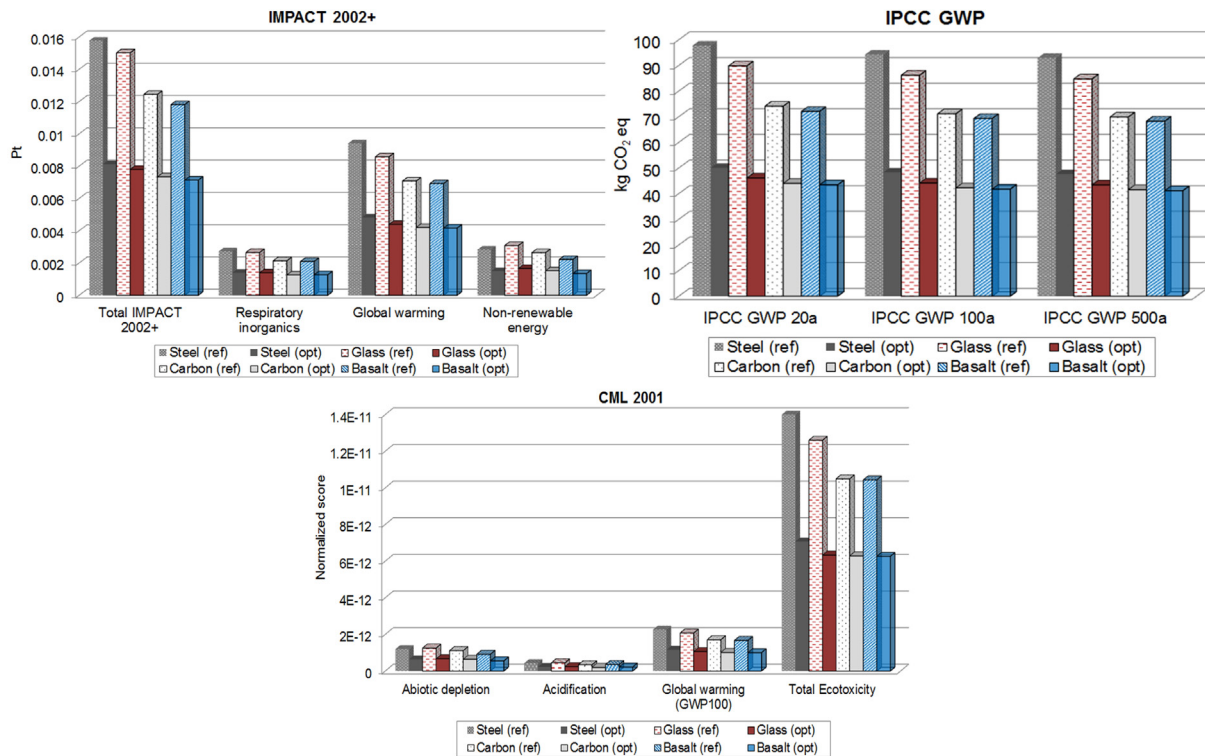

Figure 6 – IMPACT 2002+, IPCC 2007 Global Warming Potential (GWP) and CML 2001; comparison between Reference and Optimal solutions (functional unit of 1 m²).

Summarizing the results of the Case Study, some major trends can be observed. Considering only the *Reference* alternatives, variations in their environmental performances have been identified. Altogether steel reinforced concrete shows the highest environmental impacts, followed by glass reinforced concrete and carbon reinforced concrete, whereas basalt reinforced concrete seems to be the most environmentally sound specimen. One single category, namely non-renewable energy consumption is dominated by glass reinforced concrete (see also Figure 5).

Comparing *Reference* and *Optimal* alternatives, the environmental impacts of all four solutions are considerably reduced. Looking only at the *Optimal* alternatives, the variations regarding the environmental performances are becoming less significant. However, the overall trend remains: basalt and carbon reinforced concrete are identified as ecologically preferable alternatives, whereas steel and glass alternatives show greatest environmental impacts.

Moreover, the most dominant life-cycle impact categories have been identified, which are global warming potential, non-renewable energy consumption and respiratory inorganics for IMPACT 2002+ and ecotoxicity, global warming potential, abiotic depletion as well as acidification for CML 2001.

Data sensitivity

For certain materials included in the LCA analysis similar data set alternatives are available in SimaPro. The descriptions of the processes incorporated into each data set are described in the databases; however, it is still recommended to compare the available alternatives against each other in order to yield an accurate comparison in the evaluation. In the case of basalt fibres, three different cradle-to-gate processes are available and were seen as potential equivalent material data for the analysis, namely *Basalt 1-3* (see Table 3).

Table 3. Summary of data used in sensitivity analysis of basalt fibre.

Material	Equivalent Material	Database
Basalt 1	Basalt, at mine	ecoinvent v2.2
Basalt 2	Rock wool, fleece, production mix, at plant, density between 30 and 180 kg/m^3	ELCD database 3.0
Basalt 3	Rock wool, at plant	ecoinvent v2.2

In short, *Basalt 1* includes a mining step and a subsequent benefaction step comprising crushing, washing and classification. It should be noted that this module is designed for the use as raw material for rock wool [25]. As for *Basalt 2*, it represents a standard mineral product used for insulation applications in the building industry according to the applied technology [26]. In *Basalt 3*, the production is divided into the rock wool production itself and the packaging of rock wool. The underlying details and complexities included in this data set can be observed in [29]. A main limitation of this work is such that these abovementioned data sets, which are so-called equivalent materials, may in fact include or exclude processes involved in the cradle-to-gate processes for basalt fibre reinforcement. Nevertheless, the gathering of raw data representing a particular component of a building material, such as is the need in this study, is an elaborate task and beyond the scope of this work.

To observe the sensitivity of the three basalt alternatives, *Basalt 1-3*, the total cumulative energy demand as well as the environmental impact based on CML 2001 were computed and are illustrated in Figure 7 and Figure 8, respectively. In Figure 7, there is a significant difference between the total cumulative energy demand results yielded for *Basalt 1* and the two other options (99%). Accordingly, *Basalt 1* was ruled out as these data would cause a large bias in the comparison of the *Reference* alternatives. Conversely, *Basalt 2* and *3* were found to differ by only approximately 24% which is assumed to be minimal.
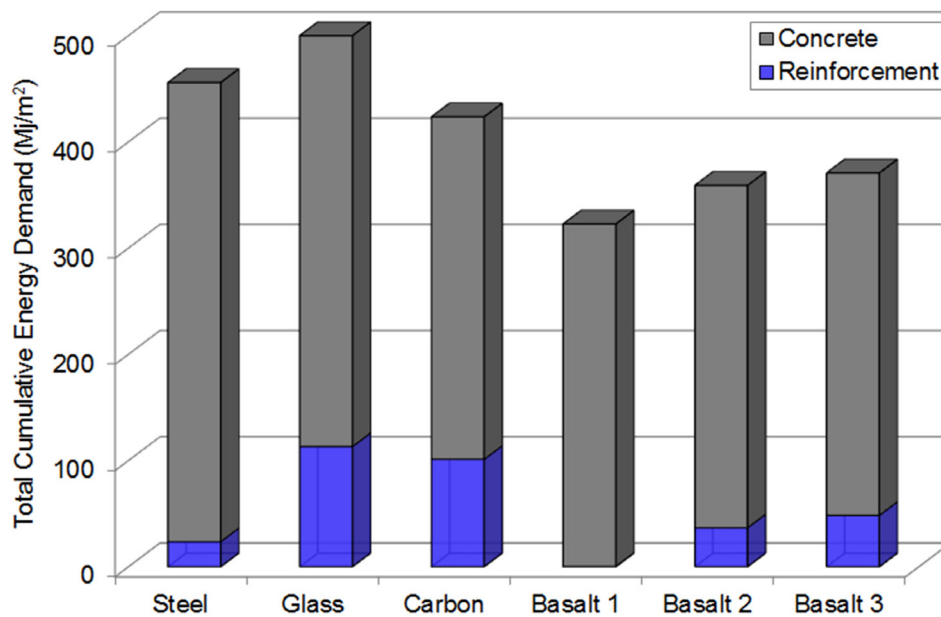
Figure 7 – Total cumulative energy demand of Reference specimens; comparison between concrete and reinforcement alternatives including Basalt 1-3 (functional unit of 1 m^2).

Moving on to Figure 8, Basalt 1 appears to have nearly null environmental impact, which once again would impose a bias in the evaluation. Concerning *Basalt 2* and *3*, there is a rather balanced outcome in the result with the exception of total ecotoxicity and human toxicity. Since *Basalt 2* was arbitrarily selected for the evaluation, the basalt and carbon alternatives were observed to be the ecologically preferable alternatives as previously mentioned in the analysis (refer to Figure 6). However, it should be pointed out that if *Basalt 3* would have been applied, that carbon could have been a superior ecological solution in terms of total ecotoxicity compared to basalt.
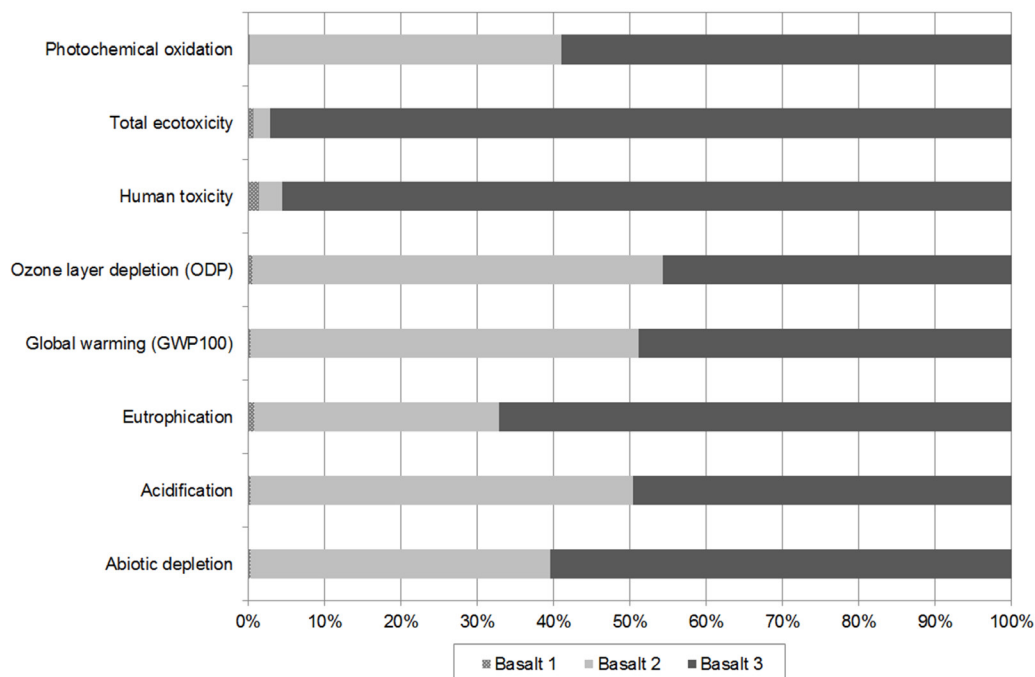

Figure 8 – Normalized CML 2001 results; comparison between Basalt 1-3 (functional unit of 1 m^2).

CONCLUSIONS AND FUTURE OUTLOOK

The presented study analyzed the environmental impacts of TRC compared to conventional steel reinforced concrete. Current applications of TRC façade elements and their sustainable potential have been presented and critically discussed. Subsequently, the LCA's results indicated the fact that TRC can be considered as more resource efficient reinforced concrete alternative particularly referring to a façade application. By requiring less amount of concrete, the cumulative energy demand throughout the life-cycle of a reinforced concrete element can be significantly reduced. Moreover, the LCA including an underpinning sensitivity analysis demonstrated lower environmental impacts of TRC, especially for the basalt and carbon specimens, in comparison with steel reinforced concrete. In summary, TRC is not only seen as an environmentally sound substitute for conventional reinforced concrete in façade elements, but also as a complement to already existing building solutions. Nevertheless, in regards to the future outlook, research on the ecological potential of TRC is to be further developed. Integrating all life-cycle phases of a building material in the LCA, i.e. extraction to end of life, could contribute to a holistic evaluation of the material's ecological performance. Besides, critical discussions about methodological choices, such as the selection of the system boundaries and implications of the choice of the functional unit are crucial in order to ensure reliability of the applied methods.

REFERENCES

1. European Commission, *Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas reduction commitments up to 2020.* Official Journal of the European Union 2009. **L 140**: p. 136-148.
2. Energy Performance of Buildings Directive (EPDB), *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.* Official Journal of the European Union 2010. **L 153**: p. 13-35.
3. Kibert, C.J., *Sustainable construction: green building design and delivery*2012: Wiley.com.
4. Orlowsky, J. and M. Raupach, *Textile reinforced concrete-from research to application.* Cement Wapno Beton, 2011. **16**(6): p. 323-331.
5. Hegger, J., C. Goralski, and C. Kulas, *A pedestrian bridge made of textile reinforced concrete.* Schlanke Fußgängerbrücke aus Textilbeton, 2011. **106**(2): p. 64-71.
6. Insu-Shell-Projekt LIFE. *Life insu-Shell-Projekt • Institut Für Textiltechnik Der Rwth Aachen.* 2009 [cited 2013 September 10]; Available from: http://www.life-insushell.de/en/das-projekt.html.
7. Ortlepp, R. and M. Curbach, *Strengthening of Columns using Textile Reinforced Concrete (TRC).* Beton- Und Stahlbetonbau, 2009. **104**(10): p. 681-689.
8. Ortlepp, R., F. Schladitz, and M. Curbach, *Textilbetonverstärkte Stahlbetonstützen.* Beton- Und Stahlbetonbau, 2011. **106**(9): p. 640-648.
9. Building Research Establishment (BRE). *BREEAM's Green Guide to Specification.* 2013 December 16, 2012]; Available from: http://www.bre.co.uk/greenguide/podpage.jsp?id=2126.

10. U.S. Green Building Council (USGBC). [cited 2013 September 15]; Available from: http://new.usgbc.org/leed.

11. Deutsche Gesellschaft für Nachhaltiges Bauen – DGNB e.V./German Sustainable Building Council. *DGNB System*. 2013 [cited 2013 December 04]; Available from: http://www.dgnb-system.de/en/system/certification_system/.

12. Regulation (EU) No 305/2011 of the European Parliament and of the Council, *Laying Down Harmonised Conditions for Marketing of Construction Products and Repealing Council Directive 89/106/Eec.* Official Journal of the European Union, 2011. **L 88/5**.

13. Mahadevan, M.G., *Textile Spinning, Weaving and Designing*2009, Chandigarh, IND: Global Media.

14. Brameshuber, W., *Report 36: Textile Reinforced Concrete-State-of-the-Art Report of RILEM TC 201-TRC*. Vol. 36. 2006: RILEM publications.

15. Malaga, K., et al. *Textile reinforced concrete sandwich panels*. in *International FIB Symposium 2012*. 2012. Stockholm, Sweden.

16. EN 1992, *Eurocode 2: Design of Concrete Structures: Part 1-1: General Rules and Rules for Buildings*2004: British Standards Institution.

17. Tomoscheit, S., et al., *Project Life INSUSHELL: Reducing the Carbon Footprint in Concrete Construction.* International Journal of Sustainable Building Technology and Urban Development, 2011. **2**(2): p. 162-169.

18. Mehta, P.K., *Reducing the environmental impact of concrete.* Concrete international, 2001. **23**(10): p. 61-66.

19. Losch, E.D., et al., *State of the Art of Precast/Prestressed Concrete Sandwich Wall Panels*. PCI Journal, 2011: p. 1.

20. Hegger, J., C. Kulas, and M. Horstmann, *Realization of TRC facades with impregnated AR-glass textiles.* Key Engineering Materials, 2011. **466**: p. 121-130.

21. ISO, E., *14040: 2006.* Environmental management–Life cycle assessment–Principles and framework, 2006.

22. ISO, E., *14044: 2006.* Environmental management–Life cycle assessment–Requirements and guidelines, 2006.

23. Pré Consultants. *SimaPro 7.3.3*. 2012 [cited 2013 September 15]; Available from: www.esu-services.ch/simapro/.

24. Williams Portal, N., et al., *Sustainable Potential of Textile-Reinforced Concrete.* Submitted to ASCE Journal of Materials in Civil Engineering, 2013.

25. Swiss Centre for Life Cycle Inventories, *EcoInvent v3.0*, 2013.

26. European Commission, *European Reference Life Cycle Database 3.0 (ELCD)*, 2013, Joint Research Centre - Institute for Environment and Sustainability

27. PRé Consultants, *SimaPro 7 Database Manual, Methods Library v.2.4*, 2010.

28. Hischier, R., et al., *Implementation of life cycle impact assessment methods.* Ecoinvent report, 2010.

29. Flury, K., R. Frischknecht, and A. Flumroc, *Life Cycle Assessment of Rock Wool Insulation.* ESU-services 2012.