J Bionic Eng 16 (2019) 742–753
DOI: https://doi.org/10.1007/s42235-019-0060-1

Journal of Bionic Engineering
http://www.springer.com/journal/42235

Bio-inspiration as a Concept for Sustainable Constructions Illustrated on Graded Concrete

Rafael Horn[1*], Stefan Albrecht[1], Walter Haase[2], Max Langer[3], Daniel Schmeer[2], Werner Sobek[2], Olga Speck[3], Philip Leistner[4]

1. *Fraunhofer Institute for Building Physics IBP GaBi*, *Stuttgart* 70563, *Germany*
2. *Institute for Lightweight Structures and Conceptual Design* (*ILEK*), *University of Stuttgart*, *Stuttgart* 70569, *Germany*
3. *Plant Biomechanics Group*, *Botanic Garden*, *University of Freiburg*, *Freiburg* 79104, *Germany*
4. *Institute for Acoustics and Building Physics*, *University of Stuttgart*, *Stuttgart* 70569, *Germany*

Abstract

The building industry is one of the main contributors to worldwide resource consumption and anthropogenic climate change. Therefore, sustainable solutions in construction are particularly urgent. Inspired by the success principles of living nature, biologists and engineers present here an interdisciplinary work: The sustainability assessment of a bio-inspired material technology called graded concrete, which was developed at ILEK. Gradient structural materials can be found in plants on different hierarchical levels, providing a multitude of creative solutions for technology. Graded concrete applies this biological concept of structural optimization to the interior structure of concrete components to minimize material and resource expenditure. To evaluate the sustainability of this innovation, a newly developed quantitative Bio-inspired Sustainability Assessment (BiSA) method is applied. It focuses on the relationship of environmental, social and economic functions and the corresponding burdens quantified basing on life cycle assessment. The BiSA of graded concrete slabs shows significant improvements over conventional concrete for the applied use case. While an overall reduction of environmental burdens by 13% is expected, economic burdens can be reduced by up to 40% and social burdens by 35.7%. The assessment of the graded concrete technology identifies its potential with regard to sustainable construction. The presented work provides a blueprint for the interdisciplinary, integrative work on sustainable, bio-inspired innovations. It shows that the synergies of bio-inspiration and BiSA within technical product development can be fruitful.

Keywords: sustainability assessment, bio-inspired sustainability, graded concrete, biomimetic promise, BiSA

1 Introduction

Anthropogenic climate change has been evidently identified as severe thread to both people and ecosystems on a global level and the reduction of anthropogenic contributions is politically accepted on global scale with almost no exceptions[1,2]. Since the construction industry plays a key role in global resource consumption and climate change, a dramatic reduction of the resource demand is one crucial step on the way towards sustainable buildings[3]. The construction industry is one of the main originators of energy related emissions. Cement production as a core element of concrete production directly accounts for 3.8% of the global greenhouse gas emissions in 2000 and grows by 42% until 2006[4–6]. As the emission is directly originated through carbonation, the substantial reduction of the Global Warming Potential (GWP) for concrete products is rather challenging[5–7]. Both innovative techniques and new conceptual designs for conventional materials and fundamentally new approaches in building design are necessary to pave the road for environmentally sound future buildings. The solution strategies to tackle this challenge can be differentiated in emission reduction, material optimization and structural optimization.

Emission reduction includes the utilization of renewable energies in production and end-of-pipe technologies such as carbon capture and storage as well as targeted carbonation at the End-of-Life[6,8]. Material optimization is a strategy to replace the high-impact substances – mainly cement – by other materials with fewer impacts. This includes recycling of concrete, re-

***Corresponding author:** Rafael Horn
E-mail: rafael.horn@ibp.fraunhofer.de

duction of the cement fraction and replacement of cement, e.g. through fly ash[9,10]. The structural design of concrete components can be optimized to ensure functionality while minimizing environmental impacts. The development of lightweight structures is nowadays an essential prerequisite for the mass reduction of load bearing structures and the consequent reduction in resource demand[11,12]. Its main strategies are material lightweight design, structure lightweight design and system lightweight design[13].

The graded concrete presented in this article was developed in a bio-inspired approach inspired by biological models in the form of gradient structure materials and lightweight constructions[15]. Therefore, structural characteristics of hierarchical organization and gradients of biological materials systems as lightweight structures were abstracted. The aim of this abstraction was to transfer and combine functional principles of lightweight construction and load-bearing capacity, while taking multifunctionality into account. The presented work is characterized by the interdisciplinary cooperation of biologists, civil engineers and sustainability experts. The scope of the first part was an analysis of similarities and differences between gradient structural materials in plants and building components. Special focus is on plant's formation of gradients on different hierarchical levels as idea generator for technical applications. The aim of the second part is to briefly describe the concept of bio-inspired sustainability assessment. The third part covers a sustainability assessment of the presented graded concrete technology compared to a conventional concrete applied at the example of a slab. To conclude, the assessment results are discussed with regard to their suitability to evaluate the success of the bio-inspired product development approach that has been applied.

2 Bio-inspiration for gradient structural materials

Mankind has been learning from nature since the beginning of human history. In modern science, bio-inspiration is categorized and structured to systematically gain insights from living nature and implement them into technical applications or processes[16,17]. This transfer is a conscious process of creativity and engineering art, even if it is solely based on an idea or inspiration from nature[18]. Within the framework of an interdisciplinary cooperation project, based on a scientific or technical question, first a suitable biological model is analyzed and in the following abstraction step the underlying functional principles are deciphered, which are then transferred into the technical application[16,17].

2.1 Gradient structures in living nature

Since plants are sessile, they need to withstand all environmental loads in their habitat. This similarity to immobile buildings makes plants suitable role models for architectural purposes. The hierarchical and modular structure of plants is a crucial success principle in biological evolution and therefore an appropriate basis for bio-inspiration[18–20]. Moreover, biological materials are often graded within these hierarchical levels, which increases the synergy between and within the various levels[21]. A strong example for such a gradient on the organ level is the continuous change of the outer shape such as the transition of the rod-shaped leaf stalk to the planar leaf blade of *Caladium bicolor* (Figs. 1a – 1d). On the tissue level the arrangement of the vascular bundles (leaf veins) is of special interest, due to their mechanical and vital function such as fluid transport and stiffening of the plant organ (Figs. 1e and 1f)[22–24]. Gradients on the cellular level occur with respect to cell size, cell wall thickness and lignification (Fig. 1g). Generally, in analogy to reinforced concrete, plants can be regarded as composite materials consisting of various matrices (parenchyma) and reinforcements (vascular bundles, fibers).

2.2 Graded concrete

Similar to the biological structures mentioned above, the design of the built environment also follows a hierarchical and modular process[15]. In contrast to these, most design approaches on component level are mono-functional focusing on the optimization of the outer shape of the component and do not allow for multi-parameter optimization. Functional gradation within concrete components offers further optimization potentials through optimization of the internal structure[25]. By manipulating the stiffness structure within

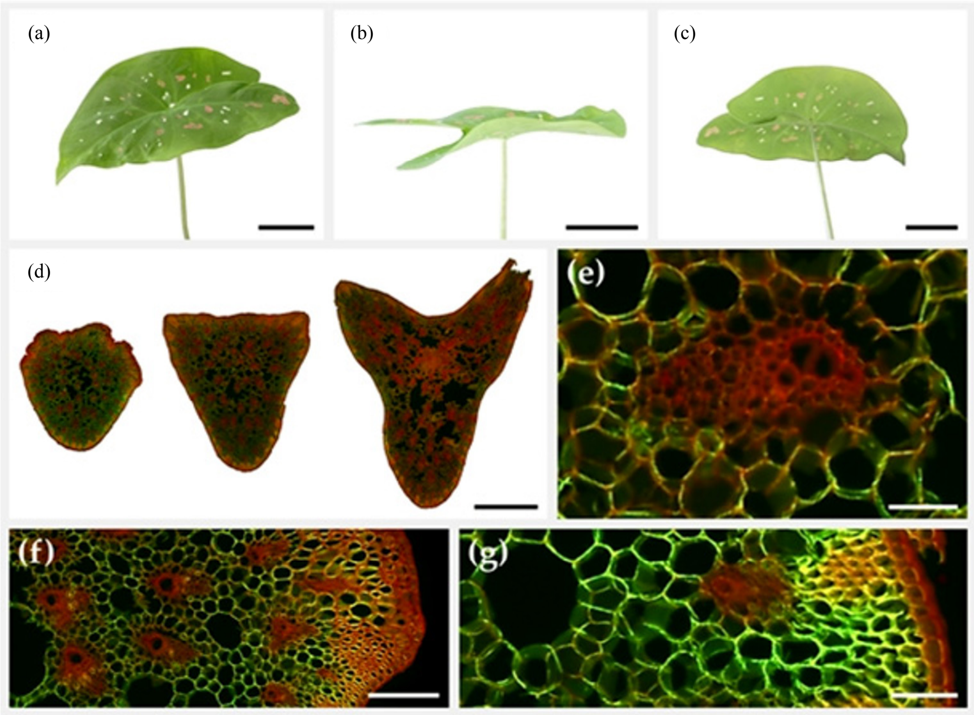

Fig. 1 Leaf of *Caladium bicolor*. (a) Top view. (b) Side view. (c) Lower side view. (d) – (g) Thin cross-sections (60 µm thickness) stained with acridine orange, whereby vascular bundles and epidermal tissue are colored red and ground tissue is dyed yellowish-green. (d) Cross-sections of the transition zone between leaf stalk and leaf blade. The round petiole (left) changes into a triangular shape (middle) and finally enters the lamina (right). (e) Gradient transition from a vascular bundle to the parenchymatous tissue with respect to cell size, cell geometry and color as an expression of lignification. (f) Arrangement and size gradient of the vascular bundles in the leaf stalk. The bundles continuously become smaller towards the epidermis (right). (g) Gradient in intercellular porosity in terms of large pores in the middle of the petiole (left) to small pores at the epidermis (right) and gradient in intracellular porosity with respect to large cells with thin cell walls in the middle of the leaf stalk (left) to small cells with thick cell walls close to the epidermis (right). Scale bars: (a) – (c) 20 mm, (d) 2 mm, (e) 70 µm, (f) 300 µm, (g) 100 µm.

components, the stress fields can be homogenized in the sense of a fully stressed design[26,27]. This principle is applied to the functional gradation of reinforced concrete components by adding porosity to the concrete matrix and, ideally, placing the reinforcing fiber in accordance with the tensile stress trajectories. By analogy with the hierarchical biological level of the cell structure with its intra- and intercellular porosity, cavities can be arranged on a micro- and/or meso-scale inside the component by using lightweight aggregates or self-developed concrete hollow spheres (Fig. 2). Due to these mineral based cavities, graded concrete represents a mono-material technology which ensures recyclability of the components at its End-of-Life.

The graded concrete technique represents a bio-inspired approach for structural components. Its development was inspired by the multi-level hierarchies and gradient structures of materials in living nature, where only principles of selected hierarchical levels were abstracted and transferred to the graded concrete (Fig. 2), such as the porosity and gradation on the cellular level (Fig. 1g). A more detailed description on graded concrete is presented in Supplement 1. The technology allows saving material while at the same time producing a structure that can withstand the given loads. In addition, the gradation allows the component to be adapted to both static and structural-physical requirements at the same time. Due to this multifunctional adaption, the use of this technology in the envelope structures of buildings such as exterior walls and roofs is promising[28].

3 Bio-inspired sustainability assessment

Biological inspirations often come along with the expectation of sustainable solutions. This phenomenon was coined by von Gleich as the “biomimetic

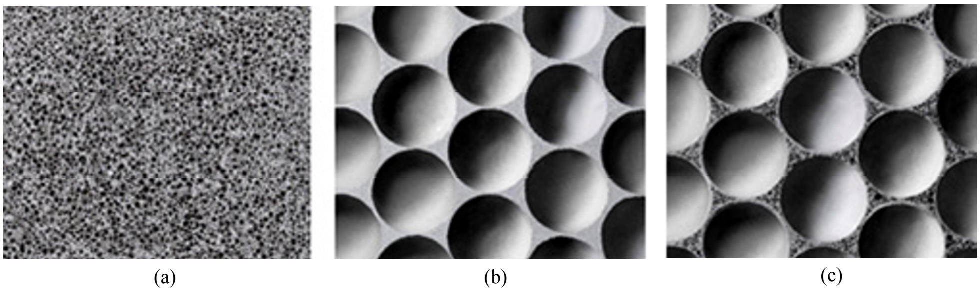

Fig. 2 Micro-gradation by choosing lightweight aggregates (a), meso-gradation by choosing mineral hollow spheres (b) and combination of micro- and meso-porosity (c).

promise”[29,30]. While this expectation is not self-fulfilling, it can be supported by an integrative sustainability assessment to identify potentials and provide decision support throughout product development. If the four elements, biological insight, knowledge transfer, development of an application and supporting sustainability assessment, are at hand, the challenge that lies within the biomimetic promise can be put into practice and bio-inspired as well as sustainable solutions can be created within a dedicated process[31]. In addition to products and processes, methods can also be developed that are inspired by the basic functioning of biological systems. Among others these are the concepts of biomimicry, environmentally benign design and Bio-inspired Sustainability Assessment (BiSA)[32–34]. BiSA was jointly designed by the authors and is able to quantitatively assess all dimensions of sustainability within a consistent model based on Life Cycle Assessment (LCA) and that is based on a specifically developed sustainability framework[31,32]. The application of life cycle thinking as a basic principle ensures compatibility with established methods to facilitate the three pillars of sustainability.

3.1 Framework

When the sustainability of a technological innovation shall be quantified, there are several requirements that have to be met by the methodological framework as well as the applied assessment model[32,35,36]. Requirements are for example the utilization of a common underlying quantitative model that ensures consistency between the assessed indicators, the consideration of positive aspects and a dedicated integration of the product development process, which are not available in existing assessment methods. Furthermore, most methods are not linked to their underlying fundamental understanding of sustainability, that frames the method and that is crucial to transparently comprehend the methods and its presumptions[37].

Therefore, a new method was jointly designed by the authors, that is able to quantitatively assess all dimensions of sustainability within a common framework and that is based on a specifically developed sustainability framework[31,32]. The underlying sustainability framework is inspired by the fundamental characteristics of biological systems, namely function and resources. It constitutes the assessment object as a system that is dedicated to fulfill certain functions by means of resource consumption. The system is defined as sustainable if it is self-preserving and the fulfilment of functions is not bought through destabilizing depletion of resources. Sustainability is thus interpreted as the dynamic component of self-sustaining[32].

3.2 Assessment model

To put the framework into practice, an assessment scheme has been created using LCA as a basis according to ISO standards 14040 and 14044[38,39], which is described in detail in Ref. [32]. The simplified LCA approach includes the obligatory steps of LCA, which are goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation[38]. In contrast to most existing sustainability assessment systems, the model is built upon one single system that is created as a life cycle inventory in accordance with LCA practice[40]. The inventory model is created using primary data complemented by background data of the database GaBi professionally available in the Software GaBi ts[41,42]. The assessment model is associated with a life cycle sustainability assessment method that has recently been

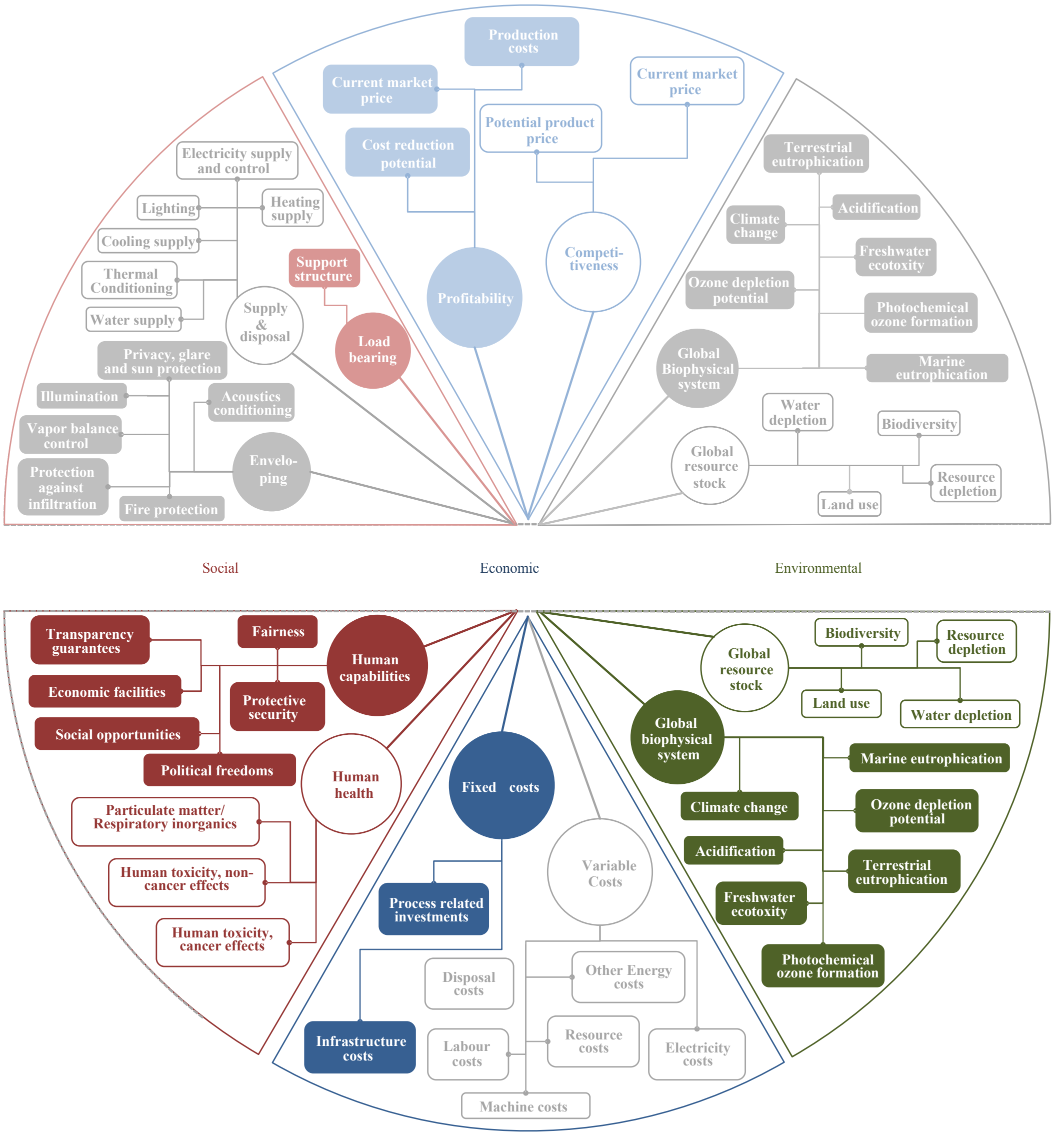

Fig. 3 Bio-inspired sustainability depicted as assessment structure. The intended functions are depicted on the upper side, indicating their positive connotation. Resource consumption is depicted as burden on the bottom side, indicating a negative connotation. Both functions and burdens are calculated for the indicators shown in the rectangular fields and normalized to a single value in the categories depicted in the bubble fields. These then add up to one relative score for each of the six aspects. Greyed out indicators are not considered in the applied case.

developed and applied at the Fraunhofer Institute for Building Physics IBP based on a reworked version of the Life Cycle Working Environment (LCWE) method[43–45]. The indicator framework is depicted in Fig. 3, showing a two-fold representation of the three dimensions, which in this way address both intended positive aspects (functions) and unintended negative aspects (burdens) of the assessed system. Within each dimension there are several main categories, each consisting of several indicators. To calculate the category values, the indicators are normalized to a reference system, aggregated to categories and weighted according to the applied methods.

4 Case study: Slabs of graded and conventional concrete

The functional gradation of concrete components is particularly promising when an inhomogeneous stress state occurs inside the components. This is usually the case with slabs and beams subject to bending stress. In

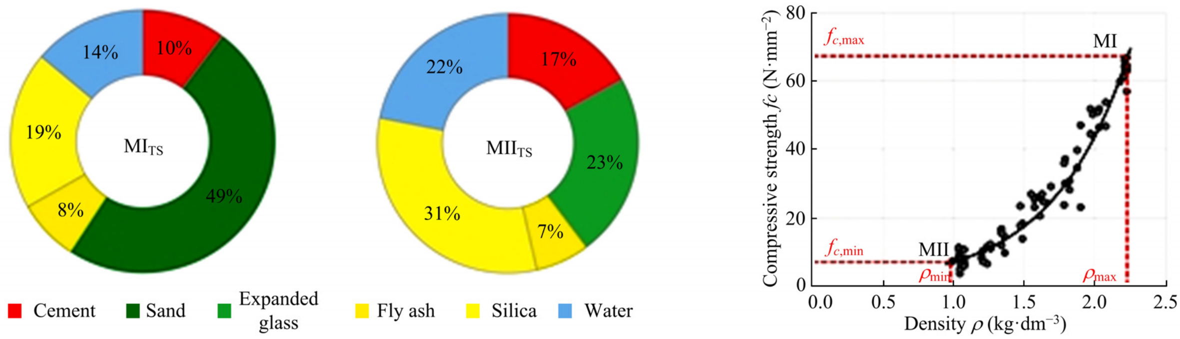

Fig. 4 Volumetric ingredients of the two concrete mixtures (left) and the possible density-compressive strength properties of the graded concrete (mixtures developed based on Ref. [46]).

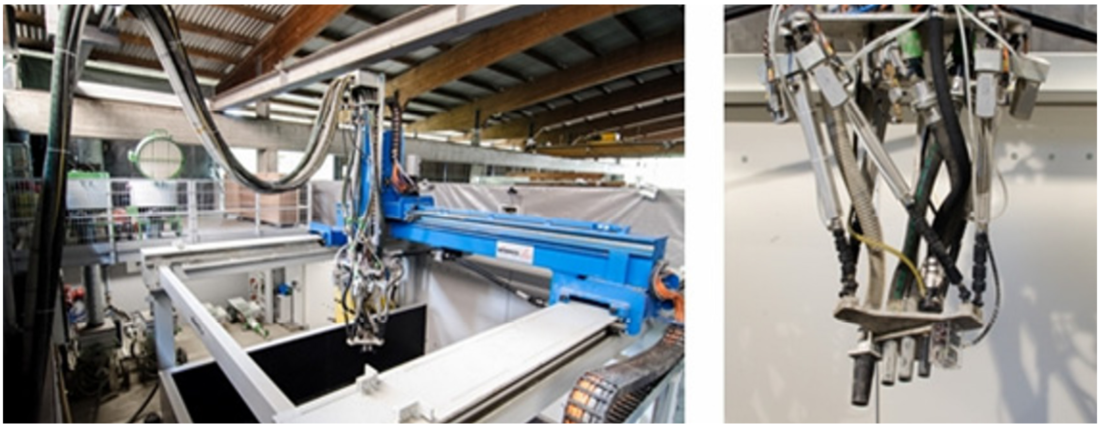

Fig. 5 Automated multi-nozzle machine for the reproducible production of graded concrete components. The two spraying nozzles are applied to one spraying head to facilitate continuous processing[28].

multi-story buildings, bending stressed slabs account for up to 70% of the construction's total mass, which is why the use of graded concrete has a high potential.

4.1 Description of the investigated component

A uniaxial spanning slab of 5 m length with across-sectional height of 0.2 m is investigated as exemplary case study. It consists of lightweight concrete (MII$_{TS}$) being placed in the low stressed regions of the building component, high-strength concrete (MI$_{TS}$) in the highly stressed regions, and a micro-gradation as a combination of the two basic mixtures in the intermediate stress regions (Fig. 4)[46]. Both mixtures consist of the same materials in different shares and have been developed at the University of Stuttgart in cooperation between the Institute of Construction Materials (IWB) and ILEK. The lower density of the lightweight mixture is reached through a change in mass shares of the basic components and the adding of alkali resistant expanded glass[47–49]. The practical implementation of the construction is carried out in an automated multi-nozzle spraying process (Fig. 5) developed in cooperation between ILEK and the Institute for System Dynamics (ISYS) at the University of Stuttgart. Two basic mixtures MI$_{TS}$ (high-strength) and MII$_{TS}$ (highly porous) are superimposed according to the stress conditions in the component and are precisely installed by means of a portal system[14,50,51].

The exemplary component that was designed and manufactured using the graded concrete dry spraying technique is accompanied by mass savings of about 30% compared to the conventional concrete slab, while complying with the same static requirements. Not to be neglected are the secondary savings due to the minimized weight of the slab. The amount of reinforcement steel can be decreased by 10% for each slab. Also, the load-transferring elements such as walls and columns can be sized down. Assuming that the whole construction weight is distributed across 70% slabs and 30% load-transferring elements, for example, in a 10-story building, the entire supporting structure and consequently also the mass of the foundation can be reduced by more than 40%.

4.2 Comparative sustainability assessment

Through the application of BiSA, the sustainability potential of graded concrete is investigated. The assessment is conducted in comparison to a conventional concrete slab of the same load bearing capacity as reference system. For the assessment the production phase including materials, energy and production processes have been investigated. The goal and scope definition that frame the case study are described in Supplement 2.

The overall results are depicted in Fig. 6. The graph shows both the intended effects of the graded concrete product system (*Function*, upper part of the graph) and the unintended effects (*Burden*, lower part) with regard to the dimensions of social, economic and environmental sustainability. In general, each of the six aspects is shown in relation to the reference system, depicted as a grey circle line. With respect to *Function*, bigger chart elements indicate a better functionality. The smaller the *Burden* chart elements the less negative impacts are caused by the system. The depicted system includes the indirect savings achieved by additional saving in the load-bearing structure.

The graded concrete component is able to fulfill the same social function, which is the technical building physical function, especially load bearing. As the economic function cannot be addressed in detail due to the developmental stage of graded concrete component as a prototypical application, the economic functionality is assumed to be equal to the reference system, which is seen as a conservative assumption due to the reduction in energy and mass-related costs. As graded concrete slabs do not fulfill an intrinsic environmental function, this chart element is not assessed. However, Fig. 6 shows significant differences with respect to the *Burdens*, visible by smaller chart elements. For the environmental burden, a direct reduction of 13% can be achieved. While a significant reduction is caused in climate change

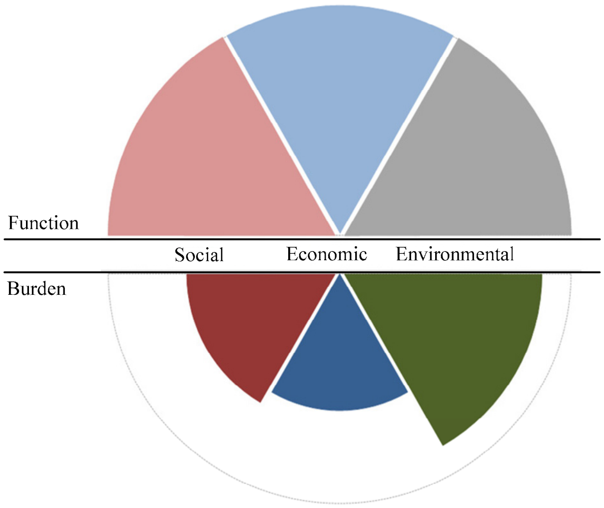

Fig. 6 Bio-inspired sustainability of graded concrete applied as slab compared to a conventional concrete slab, including indirect saving effects due to the reduced load-bearing structure. In the pie chart, social (red), economic (blue) and environmental (green) sustainability is shown as pieces of cake with different radii. Because of missing environmental functionality, the chart element environmental function is not assessed and in grey. The gray line represents the radius of the reference.

and resource depletion, the utilization of expanded glass causes a slight increase in impact on eutrophication and ozone depletion. Material and energy costs can be reduced by up to 40%. For the social burden, the reduction is up to 35.7%, mainly due to the increase in automation and the implied improved conditions in the upstream chain.

In the following, several indicators with special relevance for assessment of concrete are emphasized and depicted in further detail. This includes the environmental burden indicators of resource depletion and climate change as well as the economic burden in terms of energy, electricity and resource costs. The in-depth assessment of these indicators is fully consistent to the presented sustainability assessment and shows its hierarchical structure and its level of detail.

4.3 Assessment of resource depletion

To investigate the material resource consumption, the concept of Material Input Per Unit of Service (MIPS) is applied[52,53]. It adds up all non-renewable materials that are moved within the life cycle of a product, not only including the directly built-in mass. Fig. 7 shows the resources consumed by the investigated graded

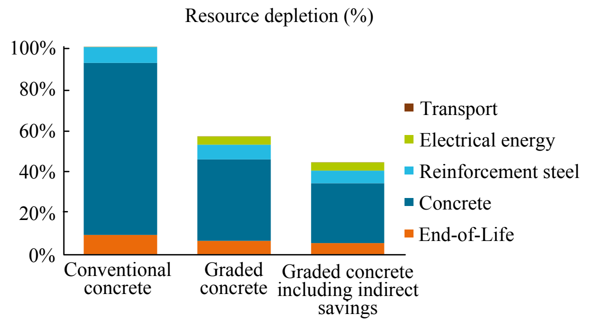

Fig. 7 Relative resource depletion of graded concrete in comparison to conventional concrete used as slab material. For graded concrete, both the direct savings relating to the slab and the indirect savings including the change in the load-bearing structure are shown. The electrical process energy impact increases for the graded concrete, but the savings in the impacts of the concrete itself by far overcompensate this.

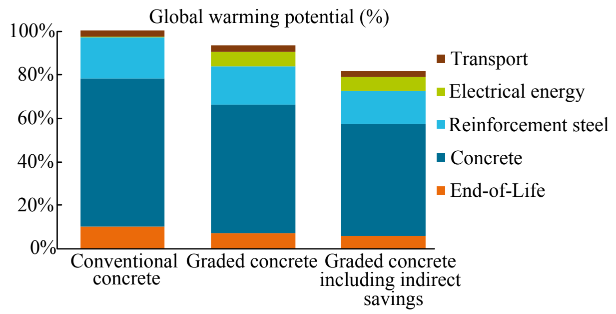

Fig. 8 Relative global warming potential of graded concrete in comparison to conventional concrete used as slab material. For graded concrete, both the direct savings relating to the slab and the indirect savings including the change in the load-bearing structure are shown. The increased impact through the production process can be compensated through the savings in GWP impact of the concrete construction.

concrete slab in relation to a conventional slab with the same building physical properties. While direct mass savings of up to 30% can be achieved, the life cycle related savings enhance the resource saving potential to 43%. These additional savings are due to utilizing recycled materials or by-products for the lightweight mixture, which are mainly expanded glass and fly ash. Conventional concrete in contrast consists to a large extent of primary materials, while construction wastes are typically used as filling materials and therefore are down-cycled. Through the application of graded concrete the required primary materials can be applied more efficiently, resulting in an overall increase in resource efficiency. The increased demand for electrical energy caused by the more complex processing is by far overcompensated by the savings in concrete caused by the graded concrete application.

Further resource saving potential due to the reduction in the load bearing structure is included in "Graded concrete including indirect savings", depicted in Fig. 7. The bar shows the maximum effect and relates to a mass share of 70% of slabs in the building. For multi-story buildings, the resource efficiency can be increased by a total of 56% when the indirect saving effect is included.

4.4 Assessment of GWP

Using graded concrete in slabs, a reduction in GWP of 7% compared to conventional concrete products can be accomplished. The reduced impacts of the concrete production are partly compensated through the additional effort in application. Through the reduced built mass, however, the impacts of End-of-Life as well as the impact of reinforcement steel are reduced. The lightweight concrete mix used and the increased power requirement for the production of graded concrete make a relatively high contribution to the greenhouse gases. Potentially, further optimization potentials are conceivable due to the turnaround in the energy policies, and thus improved environmental profiles of the power supply in the future. When taking indirect effects into account, the saving potential for GWP increases up to 19%, as less material is required for the load-bearing structure. Even though the transported masses are quite large, the transport impacts of the assessed case study are of minor relevance, especially in direct comparison with the reference (Fig. 8).

4.5 Assessment of material and energy costs

While the production process is being developed, the material and energy requirements are a possible indication for future costs, when similar processes for industrial application can be assumed in comparison to the reference system. As this is the case for graded concrete, this approach is chosen for the investigation of the cost estimation.

Fixed costs and labor costs are excluded due to the difference in the technology readiness levels and the convergence of the technologies expected by a potential market uptake of graded concrete. Material and energy costs of graded concrete are 27% lower than those of a conventional reference material, which is mainly due to the reduced demand for materials in general. Besides,

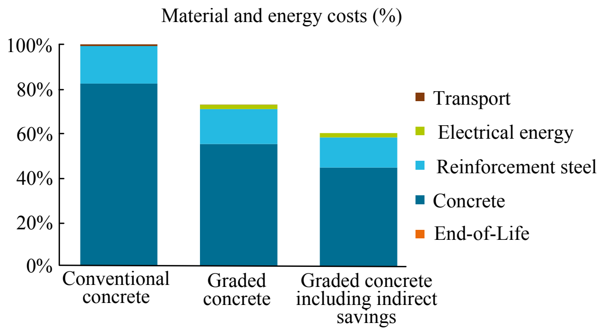

Fig. 9 Material and energy costs of graded concrete in comparison to conventional concrete used as slab material. For graded concrete, both the direct savings relating to the slab and the indirect savings including the change in the load-bearing structure are shown. As material costs are dominant in all variants, the material savings of the graded concrete variants are beneficial in terms of material and energy costs due to their reduced material demand.

this is supported by the fact that the lightweight mixture contains a higher amount of by-products, which are generally less expensive. When indirect savings are considered, the saving potential with regard to energy and material costs increases up to 40% (Fig. 9). However, while these figures indicate a generally feasible application, this does not include all production costs as the present technology readiness level does not allow a detailed assessment of the total cost structure. As the technology is developed further, these detailed cost assessments will be complemented.

5 Discussion

While the success of commercial products is mainly assessed through economic indicators such as feasibility, profitability or market penetration, this does not include many of the original motivations of the product development such as technical advancement, environmental improvement or sustainability in a broader sense[54]. This gets even more relevant when investigating products that are still under development, as their future economic performance can only be estimated through extrapolation under high uncertainty. In the following, the assessment results are discussed with regard to their suitability to evaluate the success of the bio-inspired technology development approach that has been applied.

The basic success evaluation has been conducted through life cycle based quantification of the intrinsic motivation elements resource saving, global warming potential reduction and material as well as energy cost feasibility. Bio-inspired graded concrete applied in slabs can significantly reduce the use of resources compared to the conventional precast concrete element used as a reference. Advantages are evident for all categories investigated. Compared to conventional reinforced concrete slabs the direct use of material in the building component is reduced by 30%, the use of non-renewable resources is reduced by almost 45%, and the cost of materials and energy can be reduced by almost 27%. These saving potentials are due to the reduced use of materials and the lower energy cost of the lightweight materials which could ultimately provide a feasible product when developed further. For the overall bio-inspired sustainability, advantages of graded concrete can be identified for environmental, economic and social aspects, while still providing the same function as the reference system. The most relevant influencing factors are the savings in the load bearing structure facilitated through slab weight reduction and the cement saving in the slab constituted by the structural optimization.

Both the overall bio-inspired sustainability and the in-depth investigated indicators are proving a success in development due to the given and relevant sustainability related goals. Graded concrete can, under the given framework conditions, significantly contribute to sustainable construction, to resource efficiency and reduction of global warming potential. Especially in the context of concrete construction, these potentials are of high relevance as concrete application not only is one of the main contributions to anthropogenic climate change and resource consumption, but also does not imply easily applicable strategies for their reduction[9]. As this has not been included in the International Energy Agency (IES) roadmap, graded concrete may provide a yet missing link and supporting especially the utilization of clinker substitutes and increasing the material efficiency of concrete[7].

6 Conclusion

Within the framework of the interdisciplinary cooperation projects involved, synergies of bio-inspiration, technical application and BiSA has led to a promising, more sustainable building material. The overall bio-inspired sustainability is advantageous concerning environmental, economic and social aspects. Graded concrete applied as slab can significantly provide improvements for resource efficiency, global warming potential and material and energy costs compared to a conventional slab. The most relevant influencing parameter can be identified in the indirect savings that are caused by a weight reduction of the load bearing structure. While the assessment was performed on the basis of a prototypical application, the further development and according professionalization of the production process may support these results or even disclose further potentials or fields of application. The consideration of other innovative ideas in construction and design such as adaptive constructions and computational, integrative design may bear further potentials and create pathways to resource efficient future construction.

Acknowledgment

This work was mainly done under the support of the CRC-Transregio 141 "Biological Design and Integrative Structures—Analysis, Simulation and Implementation in Architecture"/project C01 funded by the German Research Foundation DFG. Significant contributions were made under the support of the project "Leichtbau im Bauwesen" funded by the ministry of economy Baden-Württemberg based on the results of the research projects "Effiziente automatisierte Herstellung multifunktionaler Bauteile mit mineralisierten Hohlkörpern" in the scope of the priority program 1542 "Leicht Bauen mit Beton" funded by the German Research Foundation DFG and "Multifunktional gradierte Bauteile für das nachhaltige Bauen mit Beton" supported by the Baden-Württemberg Foundation. The authors thank the Wirtschaftsministerium Baden-Württemberg for the financial support of this publication.

* All supplementary materials are available at http://www.springer.com/journal/42235.

References

[1] *Climate Change* 2014: *Synthesis Report*. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2014.

[2] UNFCCC. *Adoption of the Paris Agreement*, Paris Agreement, Paris, France, 2015.

[3] *United Nations Sustainable Buildings and Construction Programme*, the 10YFP programme on sustainable buildings and construction, 2016.

[4] Baumert K A, Herzog T, Pershing J. *Navigating the Numbers*: *Greenhouse Gas Data and International Climate Policy*, World Resources Institute, Washington D.C., USA, 2005.

[5] Barcelo L, Kline J, Walenta G, Gartner E. Cement and carbon emissions. *Materials and Structures*, 2014, **47**, 1055–1065.

[6] IEA. *Cement Technology Roadmap* 2009: *Carbon Emissions Reductions Up To* 2050, IEA Technology Roadmaps, OECD Publishing, Paris, France, 2009.

[7] *Technology Roadmap Energy Efficient Building Envelopes*, International Energy Agency, Paris, France, 2013.

[8] Xi F, Davis S J, Ciais P, Crawford-Brown D, Guan D, Pade C, Shi T, Syddall M, Lv J, Ji L Z, Bing L F, Wang J Y, Wei W, Yang K-H, Lagerblad B, Galan I, Andrade C, Zhang Y, Liu Z. Substantial global carbon uptake by cement carbonation. *Nature Geoscience*, 2016, **9**, 880–883.

[9] Kim T, Tae S, Chae C. Analysis of environmental impact for concrete using LCA by varying the recycling components, the compressive strength and the admixture material mixing. *Sustainability*, 2016, **8**, 389.

[10] Amato I. Concrete Solutions: Cement manufacturing is a major source of greenhouse gases. But cutting emissions means mastering one of the most complex materials known. *Nature*, 2013, **49**, 300–301.

[11] Sobek W. Die Zukunft des Leichtbaus. Herausforderungen und mögliche Entwicklungen. *Bautechnik*, 2015, **92**, 879–882. (in German)

[12] Hamm C. *Evolution of Lightweight Structures*: *Analyses and Technical Applications*, Springer, Berlin, Germany, 2015.

[13] Sobek W. Zum Entwerfen im Leichtbau. *Der Bauingenieur*, 1995, **70**, 323–329. (in German)

[14] Wörner M, Schmeer D, Schuler B, Pfinder J, Garrecht H, Sawodny O, Sobek W. Gradientenbetontechnologie. *Beton- und Stahlbetonbau*, 2016, **111**, 794–805. (in German)

[15] Palkovic S D, Brommer D B, Kupwade-Patil K, Masic A, Buehler M J, Büyüköztürk O. Roadmap across the mesoscale for durable and sustainable cement paste – A bioinspired approach. *Construction and Building Materials*, 2016, **115**, 13–31.

[16] Speck T, Speck O. Process sequences in biomimetic research. *Design and Nature IV*: *Comparing Design in Nature with Science and Engineering*, WIT Press, Southampton, UK, 2008, 3–11.

[17] *Biomimetics – Conception and Strategy – Differences Between Biomimetic and Conventional Methods/Products*, German and English version, VDI 6220, 2012.

[18] Speck O, Speck D, Horn R, Gantner J, Sedlbauer K P. Biomimetic bio-inspired biomorph sustainable? An attempt to classify and clarify biology-derived technical developments. *Bioinspiration & Biomimetics*, 2017, **12**, 11004.

[19] Wegst U G K, Bai H, Saiz E, Tomsia A P, Ritchie R O. Bioinspired structural materials. *Nature Materials*, 2015, **14**, 23–36.

[20] Wagner G P. Homologues, natural kinds and the evolution of modularity. *American Zoologist*, 1996, **36**, 36–43.

[21] Rüggeberg M, Speck T, Paris O, Lapierre C, Pollet B, Koch G, Burgert I. Stiffness gradients in vascular bundles of the palm Washingtonia robusta. *Proceedings of Biological Sciences*, 2008, **275**, 2221–2229.

[22] Kull U, Herbig A. Das Blattadersystem der Angiospermen. Form und Evolution. *Naturwissenschaften*, 1995, **82**, 441–451. (in German)

[23] Roth-Nebelsick A, Uhl D, Mosbrugger V, Kerp H. Evolution and function of leaf venation architecture: A review. *Annals of Botany*, 2001, **87**, 553–566.

[24] McCoy R W. The anatomy of the leaf of Zeugites munroana, an anomalous grass. *Bulletin of the Torrey Botanical Club*, 1934, **61**, 429–436.

[25] Liu X, Yan M, Galobardes I, Sikora K. Assessing the potential of functionally graded concrete using fibre reinforced and recycled aggregate concrete. *Construction and Building Materials*, 2018, **171**, 793–801.

[26] Sobek W. Über die Gestaltung der Bauteilinnenräume: Meinem Freund Manfred Curbach zum 60. Geburtstag gewidmet. In: Scheerer S, van Stipriaan U. *Festschrift zu Ehren von Prof. Dr.-Ing. Dr.-Ing. E.h. Manfred Curbach.* Dresden, Germany: GWT-TUD GmbH, 2016. (in German)

[27] Alam M S, Wahab M A, Jenkins C H. Mechanics in naturally compliant structures. *Mechanics of Materials*, 2007, **39**, 145–160.

[28] Toader N, Sobek W, Nickel K G. Energy absorption in functionally graded concrete bioinspired by sea urchin spines. *Journal of Bionic Engineering*, 2017, **14**, 369–378.

[29] Gleich A, Pade C, Petschow U, Pissarskoi E. *Potentials and Trends in Biomimetics*, Springer, Berlin, Heidelberg, Germany, 2010.

[30] von Gleich A. Das bionische Versprechen. Ist die Bionik so gut wie ihr Ruf? *Ökologisches Wirtschaften*, 2007, **22**, 21–23. (in German)

[31] Horn R, Gantner J, Widmer L, Sedlbauer K P, Speck O. Bio-inspired sustainability assessment: A conceptual framework. In: Knippers J, Nickel K G, Speck T, eds., *Biomimetic Research for Architecture and Building Construction*: *Biological Design and Integrative Structures*, Springer, Cham, Switzerland, 2016, 361–377.

[32] Horn R, Dahy H, Gantner J, Speck O, Leistner P. Bio-inspired sustainability assessment for building product development – concept and case study. *Sustainability*, 2018, **10**, 1–25.

[33] Pedersen Zari M. Ecosystem processes for biomimetic architectural and urban design. *Architectural Science Review*, 2014, **58**, 106–119.

[34] Reap J, Baumeister D, Bras B. Holism, biomimicry and sustainable engineering. *ASME* 2005 *International Mechanical Engineering Congress and Exposition*, Orlando, Florida, USA, 2005, 423–431.

[35] Guinée J. Life cycle sustainability assessment: What is it and what are its challenges? In: Clift R and Druckman A eds., *Taking Stock of Industrial Ecology*, Springer, Cham, Switzerland, 2016, 45–68.

[36] Weidema B P, Ekvall T, Heijungs R. *Guidelines for Application of Deepened and Broadened LCA*, deliverable D18 of work package 5 of the CALCAS project, 2009.

[37] Ziegler R, Ott K. The quality of sustainability science: A philosophical perspective. *Sustainability*: *Science*, *Practice and Policy*, 2017, **7**, 31–44.

[38] *Environmental Management – Life Cycle Assessment – Principles and Framework*, German and English version, EN ISO 14040, 2006.

[39] *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*, *German version*, *EN ISO* 14044, 2006.

[40] *ILCD handbook - General Guide for Life Cycle Assessment*: *Detailed Guidance*, Publications Office of the European Union, Luxembourg, 2010.

[41] *GaBi ts. Sofware-System and Databases for Life Cycle Engineering*, thinkstep AG, 2017.

[42] *GaBi Databases*: *Upgrades & Improvements*, thinkstep AG, 2017.

[43] Gantner J, Beck T, Horn R. *CommONEnergy Deliverable* 5.7. *Social Impact Assessment of Shopping Mall Retrofitting*,

CommONEnergy Project, 2017.

[44] Albrecht S, Endres H-J, Knüpffer E, Spierling S. Biokunststoffe – quo vadis? uwf UmweltWirtschaftsForum, 2016, **24**, 55–62. (in German)

[45] Ko N, Lorenz M, Horn R, Krieg H, Baumann M. Sustainability assessment of Concentrated Solar Power (CSP) tower plants – Integrating LCA, LCC and LCWE in one framework. *Procedia CIRP*, 2018, **69**, 395–400.

[46] Herrmann M, Sobek W. Gradientenbeton – Numerische Entwurfsmethoden und experimentelle Untersuchung gewichtsoptimierter Bauteile. *Beton- und Stahlbetonbau*, 2015, **110**, 672–686. (in German)

[47] *Liaver*. *Expanded glass technologies*, [2017-12-29], http://www.liaver.com/en/liaver/fields-of-application/

[48] Carsana M, Bertolini L. Durability of lightweight concrete with expanded glass and silica fume. *ACI Materials Journal*, 2017, **114**, 207–213.

[49] Popov M, Zakrevskaya L, Vaganov V, Hempel S, Mechtcherine V. Performance of lightweight concrete based on granulated foamglass. *IOP Conference Series*: *Materials Science and Engineering*, 2015, **96**, 12017.

[50] Herrmann M. *Gradientenbeton*: *Untersuchungen zur Gewichtsoptimierung einachsiger biege- und querkraftbeanspruchter Bauteile*, Dissertation, Universität Stuttgart, Stuttgart, Germany, 2015. (in German)

[51] Schmeer D, Sobek W. Weight-optimized and mono-material concrete components by the integration of mineralized hollow spheres. *Proceedings of the International Association for Shell and Spatial Structures* (*IASS*) *Symposium*, Hamburg, Germany, 2017.

[52] Schmidt-Bleek F, Bierter W. *Das MIPS-Konzept. Weniger Naturverbrauch--mehr Lebensqualität durch Faktor* 10, Droemer, München, Germany, 1998. (in German)

[53] Saurat M, Ritthoff M. Calculating MIPS 2.0. *Resources*, 2013, **2**, 581–607.

[54] Hallstedt S I. Sustainability criteria and sustainability compliance index for decision support in product development. *Journal of Cleaner Production*, 2017, **140**, 251–266.