Mineral-bonded composites for enhanced structural impact safety: The vision of the DFG GRK 2250

Dr. Cesare Signorini, Prof. Dr.-Ing. Viktor Mechtcherine
Institut für Baustoffe der TU Dresden, 01062 Dresden
E-Mail: cesare.signorini@tu-dresden.de, Telefon: +49 351 463 36565

Abstract

Existing reinforced concrete structures feature, as a rule, a relatively low resistance to various sorts of impact loading, such as shock, collision, or explosion. To this aim, the primary goal of the Research Training Group (in German: *Graduiertenkolleg*, GRK) 2250, funded by the Deutsche Forschungsgemeinschaft (DFG), is to bring substantial improvements in the impact resistance of existing buildings by applying thin layers of strengthening material. By using innovative mineral-bonded composites, public safety and reliability of vitally important existing structures and infrastructure should be significantly enhanced. The scientific basis to be developed will additionally enable to build new, impact-resistant structures economically and ecologically. The framework of the GRK 2250 as well as some achievements are herein briefly presented.

1 Introduction into the GRK 2250

Reinforced concrete (RC) has been extensively investigated since the early Twentieth Century, as it represents a cost-effective solution for reliable and safe structures, from housing applications to industrial precast elements. Despite the well-known advantages brought into play by RC are now established, concrete itself is intrinsically brittle and exhibits considerable vulnerability against dynamic loading regimes. Indeed, buildings and infrastructures usually require significant safety provisions to protect goods and people when exceptional events occur, like, e.g., in the case of terroristic attacks, explosions or collisions, induced by a variety of possible causes. Against this background, the Research Training Group 2250 (in German: *Graduiertenkolleg*, GRK) was established in 2017 at the Technische Universität Dresden. In this framework, the scientific basis to be developed enables to retrofit crucial concrete structures, to become impact-resistant and resilient against catastrophic events; see schematic in Figure 1. The research framework involves and combines the conceptualisation and characterisation of new materials, and the structural assessment of full-scale elements strengthened with novel thin mineral-bonded composite layers, meeting at the same time the urgent need of an affordable and sustainable built environment [1]–[3].

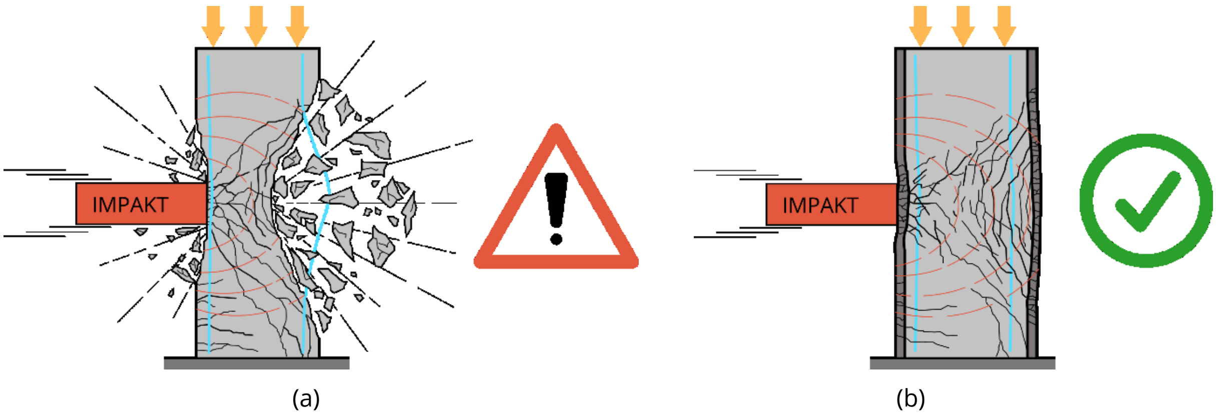


Figure 1 Impact resistance of a reinforced concrete element a) without and b) with strengthening layers made of mineral-bonded composites. Graphic: Marko Butler

The vision of the GRK 2250 consists of six parts, covering the entire span from construction materials to the structures themselves. More specifically, it concerns the development of:

- new mineral-based composites, i.e., fine-grained concretes with different types of fibre reinforcement to yield especially high resistance to impact loading,
- building concepts and measurement principles for the strengthening of existing concrete structures through thin layers of novel, highly ductile composites,
- appropriate measuring and evaluation methods for the analysis of the processes occur-ring during impact, such as wave propagation, deformation, fracture etc.,
- methods for numerically simulating the behaviour of new concrete types and strengthened structures subjected to impact loading by means of the coupling of different space and time scales,
- fundamentals for resilience evaluations, for assessing the economic and ecological aspects of strengthening measures, and principles for increasing the efficiency of evaluation and assessment methods as well,
- methods for data-driven prediction of the properties and design of concrete structures with high impact resistance.

Obviously. the impact safety of contemporary buildings and infrastructure is characterised by a high degree of complexity, which requires multifaceted expertise backgrounds. The realisation of scientific projects by the doctoral students enrolled at the Research Training Group is an integral part of the comprehensive qualification and supervision concept. The curriculum of the structured, three-year doctoral study program contains a course of lectures developed especially for the training group plus in-depth and complementary courses from among the current offerings of the DRESDEN-concept institutions as well. The entire research training group program is rounded off by annual workshops and summer schools, an international summer school per cohort, and a three-month research visit abroad at a distinguished international tutor. The pronounced cross-disciplinary structure of the GRK2250 is represented in Figure 2.

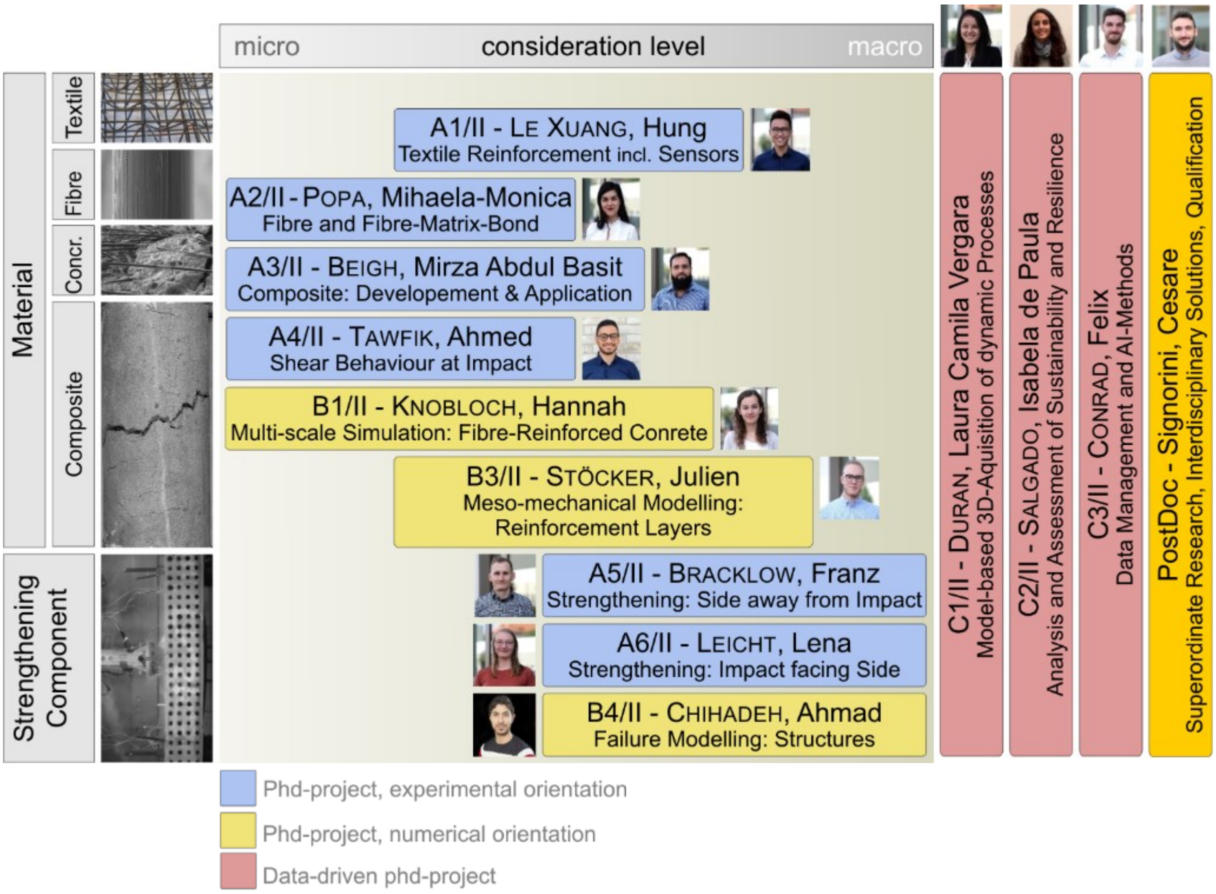


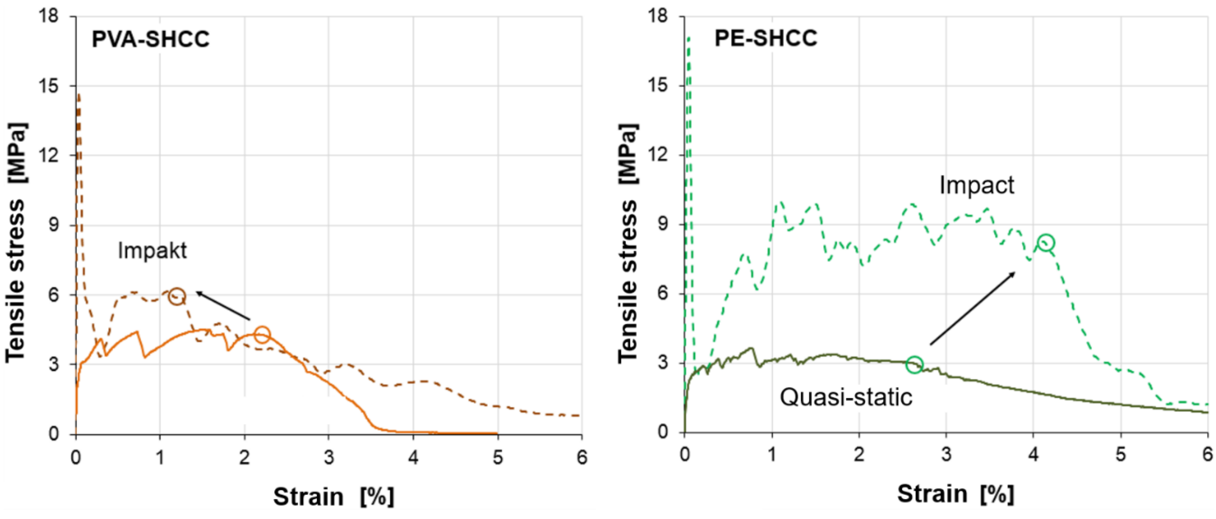
Figure 2 Individual doctoral and post-doctoral projects of the second cohort of the RTG 2250 and the general framework. Graphic: Marko Butler

2 Development of strain-hardening cement-based composites for strengthening layers against dynamic loadings

One of the spotlights has been set on the development of strain-hardening cement-based composites (SHCC) to be used as thin reinforcing layers for existing concrete structures. Dispersed polymer fibres improve the energy dissipation capability of concrete by bridging micro-cracks and triggering formation a diffused crack pattern leading to a considerable increase in ductility and load-bearing capacity [4].

The peculiar advantage of adopting fibre-reinforced materials as thin strengthening layers consists in the possibility of tailoring the mechanical parameters, like strength and stiffness of fibres and matrix, and fibre-to-matrix bond, to achieve the best performance for specific design requirements. Remarkably, the design of external strengthening layers strongly depends on the expected loading rate. Indeed, complex materials may behave very differently if subject to quasi-static or highly dynamic loading conditions. Therefore, the customary design concepts developed for quasi-static loading conditions should be rethought accordingly.

In this regard, Curosu et al. [5] compared the performance of SHCC formulations including either hydrophilic polyvinyl alcohol (PVA) or hydrophobic polyethylene (PE) fibres. This study clearly revealed how SHCC with PVA fibres are more attractive than that with PE fibres in case of quasi-static loading due to the good bond established towards the hydraulic matrix. However, the tendency is reverted when material is subject to impact loading, as PVA frictional bond is drastically altered by the dynamic nature of the loading, resulting in an unexpected and undesired strain-softening behaviour, and reduced cracking attitude, in comparison to SHCC made with PE fibres. This concept is clearly highlighted in Figure 3 [5], and emphasises once more the complexity of the material design in unconventional loading scenarios.



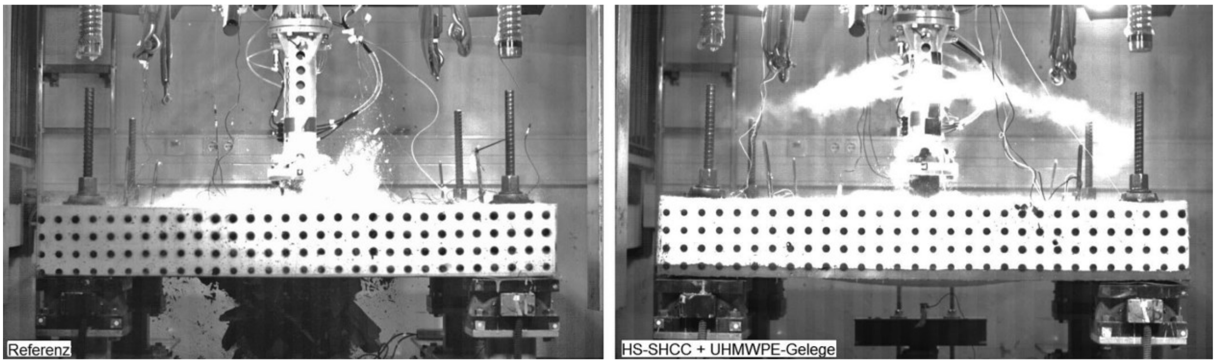
(a) (b)

Figure 3 Influence of strain rate on the tensile behaviour of normal-strength SHCC made with a) PVA-fibres and b) PE fibres. adopted from Curosu et al. [5]

SHCC micromechanics under impact is hence a crucial aspect to be considered towards the design of structural retrofitting components. To this aim, in-depth studies investigate the best engineered fibres to foster the overall dissipative capability of SHCC subjected to impact [6].

3 Hybrid composites to boost the structural safety of strengthened concrete buildings: from SHCC to textile reinforced SHCC

Textile reinforced strain-hardening cement-based composites (TR-SHCC) are hybrid composites which exhibit an exceptional dissipation performance under dynamic loading conditions. The combined action of dispersed fibres and continuous textile, both embedded into cement-based fine-grained matrices leads to an effective enhancement of bearing capacity, ductility, and crack control [7]. In synergy with the quasi-ductile nature of SHCC, textile reinforcement can effectively distribute the loading from impact acting as a membrane layer [8]. The versatility of textile design allows to address specific requirements in impact strengthening of concrete slabs and beams. For example, three-dimensional (3D) cellular textiles have been specifically conceptualised to be applied onto the impact side of concrete members. Indeed, the optimised topology of 3D textiles counting on a truss-like architecture warrants to effectively withstand highly concentrated shear forces induced by projectiles on the impact side of target concrete members [9]. Conversely, two-dimensional (2D) textiles in combination with SHCC placed as additional reinforcement on the rear side of impacted members can exert an exceptional retention action, preventing massive scabbing from the substrate. This membrane-like effect is clearly documented by high-speed camera images of full-scale impact tests, see Figure 4, [10].



(a) (b)

Figure 4 High-speed camera recordings during impact tests conducted in an 11-m-high drop tower facility, developed by Institute of Concrete Structures at the TU Dresden [12]; (a) reference plate, (b) plate strengthened by HS-SHCC and UHMWPE textile. Photos: Marcus Hering

Again, textile design needs to be performed under consideration of impact strengthening, as the bond behaviour with the surrounding SHCC matrix is susceptible to the loading rate, as demonstrated by Gong et al. [11]. Furthermore, TR-SHCC or other rigid layers are being experimentally assessed in combination with damping layers made of soft cement-based composites in order to determine the most effective strengthening strategy to shield people and goods from dynamic loading. Soft interlayers are supposed to dissipate the energy of the shock waves following the collision and reducing the portion of substrate materials abruptly ejected. Pilot studies at the structural scale clearly prove the effectiveness of such approach.

4 Economically and ecologically driven optimisation of novel strengthening technologies

Another important issue to consider while developing new materials and technologies for retrofitting of existing structures is the urgent need of sustainable and affordable solutions to be scaled up effectively. Sustainability and resilience concepts, therefore, are compelling at the same extent as performance requirements. For example, the use of high molecular weight polyethylene fibres (HMWPE) is known to enable a pronounced strain-hardening of cementitious composites [13]. However, they are expensive and characterised by disputable environmental viability. Due to this awareness, the development of engineered polypropylene (PP) fibres has been being extensively investigated in the framework of GRK 2250, attempting to enhance the strength and adhesion properties of PP embedded in mineral matrices. Innovative production techniques are effectively tuned to fabricate bi-component PP fibres including active particles on the surface to increase the roughness and the chemical affinity of the fibres and so to foster the bond with hydraulic matrices [14]. Moving to matrices, the Research Training Group is addressing the conceptualisation of viable binders with reduced cement content. Indeed, the massive Portland clinker production entails a significant footprint, especially in terms of CO_2 emissions. The development stage is moving towards binders with reduced or even zero cement content, like e.g., limestone calcined clay cement (LC^3) or geopolymers, respectively. The former envisages a minimum of 50 % cement replacement with largely available supplementary materials. The recent investigations demonstrate promising results with respect to the manufacturing of high-performance SHCC for cutting-edge automated application techniques, such as 3D printing and shotcrete technology [15].

The critical assessment of the viability of newly developed materials is of paramount importance in the framework of the GRK 2250. The investigation of sustainability and resilience mineral-bonded composites in structural refurbishment is the target of one of the doctoral projects, which is developed in close partnership between the TU Dresden and the United Nations University Flores in Dresden. A strong benchmark towards the identification of the good practices in this field is already available, documented by the extensive literature review recently conducted by Scope et al., supported by focused case studies [16].

5 Conclusions and outlook

Impact loadings on civil and industrial structures and infrastructures brings result in dramatic societal and economic costs. The mitigation of the risk associated to ballistic impact, earthquakes, rock falls, explosions, etc. is the main target of the Research Training Group 2250 (GRK 2250), funded by the German Research Association (*Deutsche Forschungsgemeinschaft*, DFG). In this contribution, the motivation and some concepts of the GRK 2250 are elucidated. Regarding the provisions from catastrophic events for the built environment, a novel retrofitting design concept is needed, based on use of fibre reinforced materials which are characterised by light weight, sustainable constituents and outstanding ductility. Currently, the existing codes mostly refer to strength-driven criteria for design, which are important, but not sufficient to warrant the integrity of structures and, even more importantly, preserve human life. The use of fibre-reinforced materials with strain-hardening behaviour is now emerging as extremely effective in enhancing impact resistance of concrete structures through externally bonded thin strengthening layers. Building upon the attained results, in-depth investigations are now planned to determine long-term performance of novel composites, in-situ diagnostic monitoring of structures through smart materials, and fine tailoring of the material parameters for an optimised design. The available datasets and simulation tools generated in the Research Training Group constitute a robust knowledge ground to be combined in a consistent framework to pursue the optimal *(i)* mechanical performance, *(ii)* risk mitigation of full-scale structures subjected to impact, *(iii)* sustainability and resilience of the strengthened structures.

Acknowledgment

The support of the German Research Foundation (*Deutsche Forschungsgemeinschaft*, DFG) within the Research Training Group GRK 2250/2 "Mineral-bonded composites for enhanced structural impact safety", project number 287321140, is gratefully acknowledged.

References

[1] Curosu, I. (2019) *Mineral-bonded composites for enhanced structural impact safety – Overview of the format, goals and achievements of the research group GRK 2250*. Proc. of the 10th International Conference on Fracture Mechanics of Concrete and Concrete Structures, IA-FraMCoS 2019. https://doi.org/10.21012/FC10.235408

[2] Hering, M.; Scheerer, S.; Curbach, M.; Vo, D. M. P.; Sennewald, C.; Cherif, C.; Liebold, F.; Maas, H.-G.; Qinami, A.; Steinke, C.; Fuchs, A.; Kaliske, M.; Curosu, I.; Mechtcherine, V. (2021) *Impaktsicherheit von Baukonstruktionen durch mineralisch gebundene Komposite: Bauteilebene*. Beton- und Stahlbetonbau 116, S. 58–67. https://doi.org/10.1002/best.202000067

[3] Curosu, I.; Mechtcherine, V.; Vo, D. M. P.; Sennewald, C.; Cherif, C.; Wölfel, E.; Scheffler, C.; Gong, T.; Heravi, A. A.; Tamsen, E.; Balzani, D.; Shehni, A.; Häußler-Combe, U.; Fuchs, A.; Kaliske, M.; Scope, C.; Günther E. (2021) *Impaktsicherheit von Baukonstruktionen durch mineralisch gebundene Komposite: Materialebene*. Beton- und Stahlbetonbau 116, S. 45–57. https://doi.org/10.1002/best.202000074

[4] Li, V. C. (2003) *On Engineered Cementitious Composites (ECC)*. Journal of Advanced Concrete Technology 1, S. 215–230. https://doi.org/10.3151/JACT.1.215

[5] Curosu, I.; Mechtcherine, V.; Forni, D.; Cadoni, E. (2017) *Performance of various strain-hardening cement-based composites (SHCC) subject to uniaxial impact tensile loading*. Cement and Concrete Research 102, S. 16–28. https://doi.org/10.1016/j.cemconres.2017.08.008

[6] Wölfel, E.; Brünig, H.; Curosu, I.; Mechtcherine, V.; Scheffler, C. (2021) *Dynamic Single-Fiber Pull-Out of Polypropylene Fibers Produced with Different Mechanical and Surface Properties for Concrete Reinforcement*. Materials 14, Art. 722. https://doi.org/10.3390/ma14040722

[7] Gong, T.; Ahmed, A. H.; Curosu, I.; Mechtcherine, V. (2020) *Tensile behavior of hybrid fiber reinforced composites made of strain-hardening cement-based composites (SHCC) and carbon textile*. Construction and Building Materials 262, Art. 120913. https://doi.org/10.1016/j.conbuildmat.2020.120913

[8] Mobasher, B.; Peled, A.; Pahilajani, J. (2006) *Distributed cracking and stiffness degradation in fabric-cement composites*. Materials and Structures 39, S. 317–331.

[9] Vo, D. M. P.; Sennewald, C.; Golla, A.; Vorhof, M.; Hoffmann, G.; Xuan, H. L.; Nocke, A.; Cherif, C. (2022) *Textile-Based 3D Truss Reinforcement for Cement-Based Composites Subjected to Impact Loading Part I: Development of Reinforcing Structure and Composite Characterization*. Material Science Forum 1063, S. 121–132. https://doi.org/10.4028/p-46f419

[10] Leicht, L.; Beckmann, B.; Curbach, M. (2021) *Influences on the structural response of beams in drop tower experiments*. Civil Engineering Design 3, S. 192–209. https://doi.org/10.1002/cend.202100040

[11] Gong, T.; Heravi, A. A.; Alsous, G.; Curosu, I.; Mechtcherine, V. (2019) *The Impact-Tensile Behavior of Cementitious Composites Reinforced with Carbon Textile and Short Polymer Fibers*. Applied Sciences 9, Art. 4048. https://doi.org/10.3390/app9194048

[12] Hering, M.; Curbach, M. (2018) *A new testing method for textile reinforced concrete under impact load*. MATEC Web of Conferences 199, Art. 11010. https://doi.org/10.1051/matecconf/201819911010

[13] Curosu, I.; Mechtcherine, V.; Millon, O. (2016) *Effect of fiber properties and matrix composition on the tensile behavior of strain-hardening cement-based composites (SHCCs) subject to impact loading*. Cement and Concrete Research 82, S. 23–35. https://doi.org/10.1016/j.cemconres.2015.12.008

[14] Popa, M.-M.; Brünig, H.; Curosu, I.; Mechtcherine, V.; Scheffler, C. (2022) *Spinability and Characteristics of Particle-Shell PP-bicomponent Fibers for Crack Bridging in Mineral-Bonded Composites*. Serna, P.; Llano-Torre, A.; Martí-Vargas, J. R.; Navarro-Gregori, J. [Hrsg.] Fibre Reinforced Concrete: Improvements and Innovations II. Springer International Publishing, Cham, S. 255–264. https://doi.org/10.1007/978-3-030-83719-8_23

[15] Wang, L.; Rehman, N.-U.; Curosu, I.; Zhu, Z.; Beigh, M. A. B.; Liebscher, M.; Chen, L.; Tsang, D. C. W.; Hempel, S.; Mechtcherine, V. (2021) *On the use of limestone calcined clay cement (LC3) in high-strength strain-hardening cement-based composites (HS-SHCC)*. Cement and Concrete Research 144, Art. 106421. https://doi.org/10.1016/j.cemconres.2021.106421

[16] Scope, C.; Vogel, M.; Guenther, E. (2021) *Greener, cheaper, or more sustainable: Reviewing sustainability assessments of maintenance strategies of concrete structures*. Sustainable Production and Consumption 26, S. 838–858. https://doi.org/10.1016/j.spc.2020.12.022