



Low-cement Strain-Hardening Cementitious Composites: Balancing mechanical performance with environmental and economic metrics

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ABSTRACT

Industry reports document a surge in cement production in recent years, reaching 4.1 billion tonnes in 2022 and resulting in significant environmental burdens. While conventional supplementary cementitious materials often fail to meet construction demands, limestone calcined clay cements (LC³) offer a promising alternative, reducing reliance on traditional raw materials while using abundant resources. This study evaluates the sustainability potential of strain-hardening cementitious composites based on LC³ binders incorporating dispersed non-metallic synthetic fibers. A cradle-to-gate life cycle assessment in combination with an extended life cycle sustainable cost analysis was used to compare three clinker-to-binder weight ratios (50%, 35% and 25%) and three types of synthetic fiber: polypropylene, polyethylene terephthalate and ultra-high molecular weight polyethylene. This analysis also considers monetized environmental externalities. A mechanical performance indicator (work-to-fracture) was prioritized as the functional unit to meet the needs of engineering practice. This integrated framework revealed trade-offs and opportunities in material selection and optimization.

1. Introduction

Concrete is the world's second most consumed material, surpassed only by water (Miller et al., 2018). Consequently, over the past three decades, global cement production volume has increased from approximately 1.42 billion metric tons to nearly 4 billion metric tons (United Nations Environment Programme (UNEP), 2019). Such an increase has major implications for the environment: for every ton of Ordinary Portland Cement (OPC) produced, approximately 0.6 to 1.0 tons of carbon dioxide (CO₂) are emitted, depending on the manufacturing process (Peng et al., 2013). One effective strategy to mitigate the high embodied carbon of these processes is the partial substitution of clinker with Supplementary Cementitious Materials (SCMs) and fillers, such as fly ash, silica fume, or furnace slag.

However, SCMs like slag and fly ash face supply and quality constraints due to stagnant steel production and declining coal use (Scrivener et al., 2018). Limestone calcined clay cement (LC³) is a binder material and a promising alternative to OPC that partially replaces conventional clinker with calcined clay and limestone. LC³ uses abundant, less energy-intensive resources while offering potential for improving mechanical strength and durability through the

pozzolanic and synergistic interactions between clay, limestone, and clinker phases (Scrivener et al., 2018).

To accurately assess the sustainability of LC³ formulations in comparison to OPC and other alternative binders, Life Cycle Assessment (LCA) remains the most comprehensive approach, as it can capture the full environmental burden of materials from resource extraction to end-of-life (International Organization for Standardization, 2006a). The environmental performance of LC³-based concrete and cement composites has been widely documented through LCA studies (Rodrigues et al., 2022; Jungclaus et al., 2024). Across this body of work, LC³ production has been shown to reduce energy demand by 15% and CO₂ emissions by 30%–40% compared to OPC (Gettu et al., 2019). A cradle-to-gate LCA by Malacarne et al. (2021) on binders reported average emissions of 516 kg CO₂-eq per tonne of LC³, approximately 38% lower than OPC, with minimal variation across different clay types. At the structural scale, Pillai et al. (2019) analyzed two RC bridge case studies and found that LC³ mixes reduced annualized CO₂ emissions by more than 80% and extended service life by a factor of ten compared to OPC-based mixes.

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Nonetheless, the broader adoption of sustainable binders usually depends on their proven cost-effectiveness. LC³ has consistently demonstrated favorable cost performance in both material manufacturing and structural applications. Recent studies highlight improved cost-efficiency per unit strength (Kanagaraj et al., 2024) and significant life cycle cost (LCC) reductions at the structural level — up to 39% over a 50-year design life — primarily due to LC³'s enhanced durability and reduced maintenance needs (Pillai et al., 2019).

Cost advantages remain evident even when environmental externalities are monetized. Huang et al. (2025) introduced a life cycle sustainable cost (LCSC) framework that combines direct material costs with monetized environmental impacts, using the willingness-to-pay method to assign economic value to categories such as Global Warming Potential (GWP), acidification, eutrophication, and resource depletion. LC³ concretes achieved 14%–29% lower sustainability costs than OPC, with a 97%–100% probability of outperforming it across both economic and environmental dimensions.

Beyond sustainability and cost considerations, the mechanical performance of LC³ blended binders has been widely investigated. It has been demonstrated that effective binder design can mitigate the reduced clinker content due to the filler effect of added calcined clay and limestone compared to conventional OPC, leading to adequate performance even at significant replacement levels. As a result, LC³ formulations are viable binders for high-strength and ductile composite materials for structural retrofitting and protection, such as for special classes of fiber-reinforced concrete, referred to as Strain-Hardening Cementitious Composites (SHCC) or engineered cementitious composites (ECC) (Wang et al., 2021). SHCC offer extremely high ductility (up to 10% tensile strain capacity) and toughness due to multiple fine crack formation, enhanced by microfiber bridging and micromechanical design, which improves durability and impact resistance (Siginorini et al., 2023). While such advanced cementitious composites can enhance resilience, their high binder demand and resource-intensive fibers highlight the need for integrated sustainability assessment. A nexus perspective helps to capture interconnected impacts on climate, soil, water and atmospheric systems (Brouwer et al., 2023), supporting more balanced material choices even when sustainability and resilience objectives diverge (de Paula Salgado et al., 2025b).

This study responds to those needs by pursuing a threefold objective. First, it compares the environmental impact of three LC³-based binders, each with a different clinker substitution level (50%, 35% and 25% by weight) and combined with three synthetic fiber types — ultra-high molecular weight polyethylene (UHMWPE, referred to as “PE”), PP, and PET — in SHCC systems. Second, it uses a performance-based reference using work-to-fracture to assess energy absorption capacity relative to the environmental burden, thereby aligning impact assessments with structural function. Third, it incorporates both direct procurement costs and monetized environmental externalities, allowing for an added perspective on cost factors. Through this framework, the study aims to identify optimized SHLC⁴ composites that balance sustainability, mechanical performance, and economic feasibility.

To this effect, a cradle-to-gate LCA was conducted to quantify the environmental impact of seven different SHLC⁴ mixes based on the experimental works of Ahmed et al. (2024b, 2025). Although nine formulations were initially considered, two PET-based mixes were excluded due to fiber degradation in highly alkaline environments. The analysis employed two FUs: 1 m³ of composite for volumetric impact and work-to-fracture for mechanical efficiency. While volume-based FUs are common in LCAs of cementitious materials, work-to-fracture offers a more representative measure for materials subjected to impact or tensile loading.

To support this analysis, the following sections are structured as follows: Section 2 describes the raw materials, composite formulations, and details the tensile testing procedures used to quantify work-to-fracture. The LCA framework, including system boundaries and functional unit selection, is outlined in Section 3, followed by the approach

for monetizing environmental impacts in Section 4. Section 5 presents the overall results and discussion, including the sustainability assessment with two functional units (Section 5.1), along with the direct and external costs for each SHLC⁴ mix (Section 5.2.2). Finally, Section 5.3 discusses the trade-offs between environmental, economic, and mechanical performance across formulations.

2. Materials and methods

2.1. Raw materials and formulations

Three strain-hardening limestone calcined clay composites, hereafter abbreviated as SHLC⁴, were developed with varying clinker content — 50%, 35%, and 25% by weight — referred to as SHLC⁴-50, SHLC⁴-35, and SHLC⁴-25. These mix designs and their corresponding fiber reinforcements were adapted from prior experimental work by Ahmed et al. (2024b, 2025), which served as the mechanical and compositional baseline of this study. The detailed inventory data for each material and mix design, including quantities and data sources, are presented in Section 3.5.

The materials used in all mix designs were sourced from suppliers in Germany and neighboring countries. Cement (CEM I 52.5 R-SR3/NA) was obtained from Holcim GmbH (Lägerdorf, Germany), while limestone (Saxodol 90 LE, $d_{50} \approx 20 \mu\text{m}$) was procured from Sh Minerals GmbH (Heidenheim an der Brenz, Germany). Calcined clay (with ≤ 25 wt% kaolinite) was provided by Liapor GmbH & Co. KG (Hallerndorf, Germany), and gypsum from Grüssing GmbH (Filsum, Germany). Quartz sand (60–200 μm) was sourced from Strobel Quarzsand (Freihung, Germany). A polycarboxylate-based superplasticizer (MasterGlenium ACE 460) and a viscosity-modifying agent (Unterwasser-Compound 100) were used to optimize the fresh mix properties, supplied by Master Builders Solutions (Staßfurt, Germany) and Sika Deutschland GmbH (Leimen), respectively. PE fibers (Dyneema SK78) were obtained from DSM in the Netherlands, PP fibers (Asota AFC/MCP) from IFG Asota GmbH in Austria, and PET fibers from Advansa in Germany.

The formulations were tailored to promote strain-hardening behavior across all fiber types. A relatively high water-to-binder ratio was adopted to improve workability and ensure uniform fiber dispersion. In combination with increased proportions of limestone and calcined clay, this also lowered matrix strength and packing density, creating well-distributed internal flaws that promoted crack initiation and strain-hardening. A low sand-to-binder ratio (0.23) further reduced matrix toughness, improving the conditions for multiple microcrack propagation and adequate fiber activation in multiple crack flanks.

Three synthetic fibers were employed for reinforcement: PE, PP, and PET. PE fibers were selected for their superior mechanical properties in SHCC applications, including high tensile strength (~ 3400 MPa) and Young's modulus (~ 120 GPa) (Yun et al., 2013; Zhang et al., 2020), whereas PP and PET were chosen for their ductility, cost-effectiveness and sustainability benefit; PET, in particular, stands out for its availability and potential for recycling (Lin et al., 2018). To account for the lower tensile strength of PP and PET fibers (≤ 400 MPa) compared to PE fibers, their volume fractions were increased to 2.5%, while PE was used at 2.0%. These proportions were kept constant across all binder replacement levels (25%, 35%, and 50%). Table 1 summarizes the physical, geometric, and mechanical properties of the three fiber types. These values are sourced from the manufacturers' data-sheets (EuroFibers, 2012; I.F.G. International Fibres Group, n.d.; ADVANSA, 2020), when available, and from the values reported in Ahmed et al. (2025) from previous experimental characterization (values in parentheses).

Despite the unique advantages of PET fibers, their long-term stability in highly alkaline environments remains a concern. Ahmed et al. (2024b) showed that PET fibers exposed to cementitious matrices with

Table 1
Properties of PE, PP, and PET fibers used in this study.

Type of fiber	PE	PP	PET
Manufacturer, country	DSM, The Netherlands	IFG Asota, Austria	ADVANSA, Germany
Brand name	Dyneema SK78	Asota AFC/MCP	ADVA® Shortcut, ADVA® Tow
Length (mm)	12	12	6, 18, long tow
Diameter (μm)	18	18	18 (17 ± 0.69)
Tensile strength (MPa)	3400	≥ 400	584.8 ± 34.8
Young's modulus (GPa)	~ 120	n.a.	12.3 ± 6.9
Elongation at break (%)	3.5	≤ 80	34 (31.8 ± 3.3)
Density (g/cm ³)	0.97	0.91	1.37

pH ≥ 12.5 experience progressive deterioration due to alkaline hydrolysis, which leads to molecular chain scission, surface pitting, and a reduction in tensile strength and diameter over time. While tailored matrices with high levels of limestone and calcined clay (i.e., SHLC⁴-25) have demonstrated a potential to limit such degradation, formulations with higher clinker content (such as SHLC⁴-50 and SHLC⁴-35) are more alkaline and were shown to accelerate PET degradation. This deterioration compromises the long-term mechanical integrity of PET-reinforced SHCCs in high-alkalinity environments and makes SHLC⁴-50 and SHLC⁴-35 unsuitable for structural use under such conditions.

By contrast, PP fibers offer excellent durability in alkaline environments. However, their hydrophobic nature and smooth surface often result in weak fiber–matrix bonding and strain-softening behavior (Ahmed et al., 2025). In the present SHLC⁴ matrices, the irregular morphology of the limestone and calcined clay particles provided adequate pull-out resistance (Ahmed et al., 2024a), and combined with the reduced matrix density and toughness, these features promoted early-age cracking and enhanced the effectiveness of PP fibers in bridging microcracks, enabling strain-hardening behavior even with their inherently lower tensile strength and modulus.

2.2. Experimental setup and work-to-fracture

The tensile testing datasets used in this study are taken from recent works by the authors, which report the full methodological details. These details are briefly recalled here for convenience. Specifically, the tensile test result datasets for SHLC⁴ with PP and PE fibers are taken from Ahmed et al. (2025), and the dataset for SHLC⁴-PET is from Ahmed et al. (2024b). No new tensile tests were performed, and the published data were processed to compute work-to-fracture, the key functional unit, as elucidated in detail in Section 3.3.

All specimens were prepared using 3-liter batches mixed in a planetary mixer (Hobart N50). Dumbbell-shaped specimens were cast in steel molds and featured a total length of 250 mm and a gauge length of 100 mm. The cross-section was 24 mm × 40 mm over the gauge portion and smoothly transitioned to 40 mm × 40 mm at the clamping areas. The specimens were cast in layers and compacted using a top mold insert to promote fiber alignment along the tensile direction. After 28 days of curing, specimens were tested under displacement control (0.05 mm/s) using an Instron 8802 universal testing machine with rigid mechanical grips. At least four replicates were tested per fiber–matrix combination (Ahmed et al., 2025). Axial strain was measured via digital image correlation (DIC), enabling precise detection of crack formation and propagation (stereo-DIC, 2 Hz acquisition Ahmed et al., 2025).

3. Life cycle assessment

LCA is a method used to assess the environmental impact of a product, process, or activity throughout its entire life cycle. In accordance with ISO 14040 and ISO 14044 (International Organization for Standardization, 2006a,b), the assessment typically involves four key steps: defining the goal and scope, compiling a Life Cycle Inventory (LCI), performing a Life Cycle Impact Assessment (LCIA), and interpreting the results.

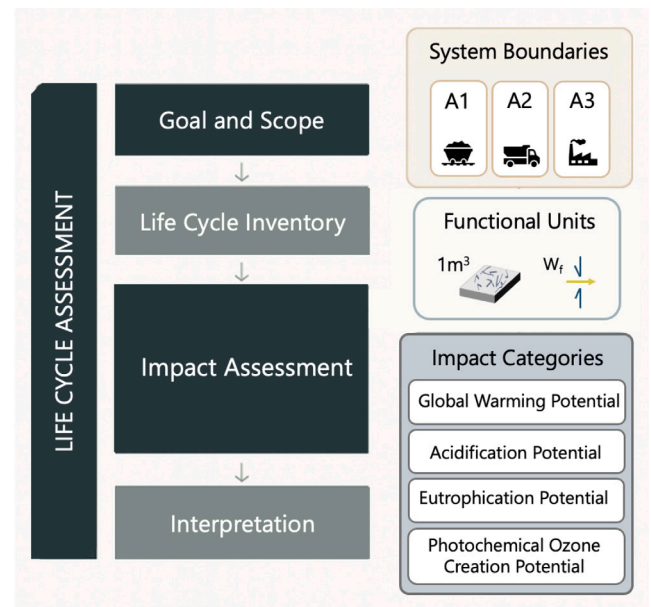


Fig. 1. LCA goal and scope overview for the current study.

3.1. Goal and scope

This study assesses the environmental impact of seven variants of SHLC⁴ using Sphera's LCA for Experts software (formerly GaBi Professional). Three fibers — PP, PE, and PET — were incorporated into LC³ formulations with varying clinker content: LC³-50, LC³-35, and LC³-25. As illustrated in Fig. 1, this study followed a cradle-to-gate system boundary (A1–A3), employed two functional units (1 m³ and work-to-fracture), and evaluated environmental performance across four impact categories: GWP, Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Creation Potential (POCP). Such impact categories are especially relevant to cement and fiber production, and are strongly influenced by emissions from clinker manufacture, combustion-related pollutants, and the release of volatile organic compounds (VOCs) (Huang et al., 2025). When considered together, these indicators can be interpreted as proxies for four interconnected environmental dimensions within the nexus — climate (GWP), soil and terrestrial chemistry (AP), water quality (EP), and atmospheric chemistry/biota (POCP).

To also account for mechanical performance, the environmental impact was analyzed in relation to work-to-fracture, a parameter that reflects the material's energy absorption before fracture (for more details, see Section 3.3).

3.2. System boundaries

In the LCA framework, the system boundaries define which life-cycle stages and processes are included in the analysis. In our work,

it follows a cradle-to-gate approach, covering raw material extraction (A1), transport to the manufacturing site (A2), and production (A3).

All processes were modeled using GaBi background datasets. Cement production reflected German industry averages and included quarrying, pyroprocessing, and grinding. Limestone, quartz sand, and gypsum were modeled as mined and processed materials, with gypsum partially sourced from flue gas desulfurization. Calcined clay was modeled as thermally activated kaolinitic clay with a Rest-of-World source (RoW; in this dataset, it is represented by Brazil); admixtures were based on Deutsche Bauchemie EPDs. PE, PP, and PET fibers were modeled using industrial polymerization and spinning processes, including gas-phase polymerization for high-density polyethylene (HDPE) and PP, and polycondensation for PET. Typical energy use and material losses were accounted for.

All datasets included region-specific modeling of electricity and thermal energy, with upstream emissions, transmission losses, and national energy sourcing considered. Allocation followed GaBi conventions: economic allocation for SCMs, market value for by-products like gypsum, and mass-based allocation where applicable.

3.3. Functional unit

The functional unit (FU) is a critical component of LCA, defined as the “quantified performance of a product system for use as a reference unit” (International Organization for Standardization, 2006a,b). It provides a standardized basis for comparison, ensuring that assessments accurately reflect the intended function of the product or system (Panesar et al., 2017). It can, however, vary significantly even within the same field, ranging from one cubic meter of concrete to an entire building designed for a 75-year service life, as highlighted in literature reviews and case studies on RC infrastructure (Scope et al., 2021; Panesar et al., 2017). Inconsistencies in FU selection can hinder cross-study comparisons and prevent direct result comparisons (Scope et al., 2021; Panesar et al., 2017).

To address these challenges, this study employs two distinct FUs:

- A volume-based FU (1 m³ of composite) to ensure comparability with existing studies.
- A performance-based FU (work-to-fracture) to reflect the material's ability to absorb tensile energy, which is more relevant for applications requiring high energy absorption and crack resistance.

Volume-based FUs are widely used because they provide a straightforward measure of environmental impact per unit of material produced. However, they fail to capture variations in mechanical efficiency, especially for materials designed for enhanced durability, toughness, or crack resistance. Performance-based FUs, in contrast, allow practitioners to account for mechanical behavior, thereby bridging the gap between material-scale assessments (mass or volume-based impact calculations) and structural-scale evaluations (which consider the total material required for constructing and maintaining a component throughout its service life), as noted by Damineli et al. (2010).

While fracture toughness (related to a material's resistance to crack propagation), as well as work-of-fracture and impact energy (related to energy dissipation during failure) are commonly used to characterize mechanical performance of fiber-reinforced composites, their incorporation as functional units in LCA remains rare. The most relevant examples include the works by Chiaia et al. (2014) and Nikbin et al. (2022), in which the authors normalized environmental impacts (GWP, embodied energy) by a fracture-related mechanical performance metric. Chiaia et al. (2014) introduced the Eco-Mechanical Index (EMI), which quantifies the sustainability of structural concrete by integrating fracture toughness (work-of-fracture in compression and bending) with embodied energy and CO₂ emissions. Similarly, Nikbin et al. (2022) incorporated impact resistance of fiber-reinforced concrete, evaluated

Table 2

Measured work-to-fracture values for different SHLC⁴ composite formulations.

Mix Design	Work-to-Fracture (kJ/m ³)
SHLC ⁴ -PE-50	142.3 ± 26.9
SHLC ⁴ -PE-35	103.6 ± 21.0
SHLC ⁴ -PE-25	69.6 ± 33.8
SHLC ⁴ -PP-50	39.5 ± 17.1
SHLC ⁴ -PP-35	60.2 ± 18.3
SHLC ⁴ -PP-25	104.6 ± 34.8
SHLC ⁴ -PET-25	125.6 ± 37.0

through drop-weight tests, into their LCA by normalizing GWP against impact energy. More recently, de Paula Salgado et al. (2025a) applied a combined LCA and machine learning framework to optimize impact-resistant, mineral-bonded composites, directly linking energy dissipation under impact loading to environmental performance.

Selecting a FU for LCA inevitably reduces the multifunctional nature of materials to a single measurable parameter. However, this simplification is necessary to enable fair and meaningful comparisons between alternatives. In the context of protective composites, *work-to-fracture* was chosen as the representative property for the performance-based FU rather than tensile strength or fracture toughness. Indeed, SHCCs, tensile strength alone is insufficient to characterize material performance. Since these pseudo-ductile composites are intended for protecting structures, tensile strength must be considered alongside strain capacity and energy absorption for a more accurate representation. On the other hand, fracture toughness (determined on pre-notched fiber-reinforced concrete (FRC) specimens to localize a single dominant crack) is less representative of the characteristic multiple-cracking and fiber-bridging response of SHCC (Curosu et al., 2022). On the contrary, work-to-fracture is a comprehensive performance measure representing the total energy dissipated during the entire tensile loading history, reflecting and merging contributions from matrix cracking, fiber bridging, fiber elongation, interfacial debonding, pull-out, and the formation of multiple cracks, which are key aspects for impact-resistant applications in structural engineering (Curosu et al., 2017).

Work-to-fracture (W_f) was calculated as the area under the stress-strain curve up to the onset of strain-softening, representing the energy absorbed per unit volume prior to fracture:

$$W_f = \int_0^{\epsilon_u} \sigma(\epsilon) d\epsilon$$

where $\sigma(\epsilon)$ is the tensile stress as a function of strain ϵ , and ϵ_u is the ultimate strain at the onset of softening.

The measured work-to-fracture values for each SHLC⁴ formulation are summarized in Table 2. The energy absorption capacity of the composites is significantly influenced by fiber type, clinker content, and microstructural interactions (Ahmed et al., 2023). For mixes reinforced with PE fibers, work-to-fracture decreases with clinker reduction, as stated by Ahmed et al. (2025), because the denser LC³-50 matrix provides firmer interfacial frictional bonding for stiff, high-strength PE fibers. On the other hand, the looser microstructure of more diluted matrices (LC³-35 and LC³-25) impairs friction with PE fibers, thereby lowering fiber-matrix bond performance. In contrast, SHLC⁴ reinforced with PP fibers showed improved performance as clinker content decreased, with SHLC⁴-25-PP achieving the highest value among the PP series. This remarkable trend is secured by the compliant nature of the PP fibers compared to the PE counterpart, which improves micromechanical compatibility with low-clinker matrices. This property extends naturally to the SHLC⁴-25 with PET fibers, which notably offered improved mechanical performance, achieving a work-to-fracture comparable to PE-based mixes and superior to all PP-based ones, indicating its viability in low-clinker systems.

This pattern reflects the fact that compliant, lower-strength PP and PET fibers develop more favorable micromechanical compatibility

in the less-dense LC³-25 matrix, where balanced bonding promotes controlled debonding and pull-out; in stronger matrices (LC³-35/50), these fibers tend to rupture prematurely rather than pull-out, limiting energy dissipation.

3.4. Assumptions and limitations

Several assumptions and limitations should be acknowledged when interpreting the results of this study:

- In compliance with the typical approach adopted in the literature for SHCC and FRC (Leon-Miquel et al., 2023; Van den Heede et al., 2018), the system boundaries were defined according to a cradle-to-gate scope (A1–A3). The assessment covers raw material extraction, transport to the manufacturing site, and production. The analysis of end-of-life phases was excluded due to the absence of reliable data on long-term performance and disposal of novel composites. Although a cradle-to-grave assessment would be the most comprehensive approach, it is typically undertaken when service life is a component of the functional unit and long-term performance can be reliably modeled (Keoleian et al., 2005; Hajiesmaeili et al., 2019; Habert et al., 2013). Consequently, the results should be interpreted in light of this scope boundaries.
- As is common in LCA studies, process data for individual materials were modeled using the closest available datasets in the database. However, these proxies may not fully reflect the specific characteristics of the laboratory-scale materials under study. In particular, UHMWPE fibers (Dyneema SK78) were represented using a polyethylene fiber dataset (HDPE/PE-HD), which does not capture the higher energy requirements and advanced processing steps (such as gel-spinning) associated with UHMWPE. Consequently, this proxy likely results in an underestimation of both energy use and emissions compared to actual Dyneema SK78 production. Calcined clay and chemical admixtures were similarly modeled using the most comparable commercial production datasets. Where no direct datasets existed, proxy processes were selected to maintain consistency across the modeling framework.
- Aggregated background datasets were used in the modeling, thus integrating raw material extraction (A1), transport to the manufacturing site (A2), and production (A3) into a single process. Accordingly, transport distances and modes are embedded in the datasets rather than reported separately. These aggregated values reflect typical conditions for freight delivery within the German construction sector, and are appropriate for simulating upstream supply chain emissions on a large scale.
- Several performance requirements must be satisfied at the material level of design. One key aspect is fresh-state processability, such as adequate sprayability. In the hardened state, long-term performance and durability over the intended service life of the material are central parameters for life cycle assessment, alongside conventional 28-day mechanical performance. This study focuses on resistance and cost, assuming that all seven compositions show comparable durability and fresh-state processability. With these simplifying assumptions, differences in environmental and economic indicators can be attributed to the choice of mix design and fibers.

3.5. Life cycle inventory

The LCI provides a detailed account of all inputs and outputs within a system, including material flows. In our work, the LCI data were modeled using the LCA for Experts software and its associated databases. The datasets were primarily sourced from the Professional database, Extension Database XIV: Construction Materials, and Extension Database XXII: Carbon Composites. Additionally, data for PE fibers (HDPE/PE-HD) was obtained through a data-on-demand request from

the MLC Database Premium - Plastics. The LCI of calcined clay was modeled using the Ecoinvent database (Wernet et al., 2016). The choice of German datasets reflected the manufacturing location.

Material flows of clinker, calcined clay, limestone, gypsum, quartz sand, admixtures, and synthetic fibers (PE, PP, PET) were specified according to the formulations described in Section 2.1. Table 3 presents their life cycle inventories, along with the corresponding processes and data sources.

3.6. Impact assessment

In the impact assessment phase, LCI environmental inputs and outputs are assigned to specific impact categories, and characterization factors are applied to quantify their contributions in common reference units (e.g., kg CO₂-eq for GWP). The process results in indicator scores per category, which can then be normalized and weighted if desired (International Organization for Standardization, 2006a,b). In our study, we applied the Centrum voor Milieukunde Leiden (CML) method (Guinée, 2001). The CML method is particularly suited for studies focused on European conditions and allows for comparative analysis of multiple environmental problems at an intermediate (midpoint) level.

4. Monetary valuation

Monetary valuation, as applied in this study, follows the guidance of ISO 14007 (International Organization for Standardization, 2019a) and ISO 14008 (International Organization for Standardization, 2019b) and is understood as the approach for assigning monetary values to changes in environmental impacts and related environmental aspects. Since non-market goods (e.g., biodiversity, clean water) lack a market price, the focus is on estimating the value of changes in their availability or quality, rather than determining their total or intrinsic worth (Pizzol et al., 2015). Valuation methods are commonly categorized into three groups, i.e., (i) observed market prices, (ii) cost-based approaches (e.g., abatement or restoration costs), and (iii) preference-based approaches, which estimate individuals' willingness to pay (WTP) to avoid or mitigate environmental harm. The latter includes both revealed preferences, derived from actual market behavior (e.g., travel cost, hedonic pricing), and stated preferences, based on hypothetical scenarios such as contingent valuation or choice experiments (Pizzol et al., 2015; Amadei et al., 2021; Finnveden et al., 2006). Damage cost methods quantify the economic consequences of environmental degradation, while abatement cost models assess the expenses associated with mitigating or avoiding these impacts.

The principle of expressing environmental impacts in a common unit is also central to the weighting phase of LCAs, where impact categories are made comparable by applying numerical factors based on value choices, which may be monetary or non-monetary in nature (Finnveden et al., 2006). Monetary valuation is often applied at this stage, and facilitates trade-off analysis and aggregation (Pizzol et al., 2015). However, not all monetary valuation methods are equally suitable for LCA. Observed- and revealed-preference approaches are often constrained by their dependence on specific market contexts or mitigation scenarios. In contrast, stated preference approaches, particularly choice experiments and budget constraints, are more appropriate for capturing both use and non-use values within the generalized, system-level perspective of LCA (Pizzol et al., 2015).

As noted by Amadei et al. (2021), the coexistence of multiple valuation methods and assumptions complicates the selection of consistent monetary valuation coefficients (MVCs) — that is, conversion factors used to express environmental impacts in monetary terms — across impact categories. Even when comparable units and approaches are used, MVCs can vary by one to three orders of magnitude, depending on the impact category (Amadei et al., 2021; Pizzol et al., 2015). To ensure internal consistency and to avoid defining a new set of MVCs ad

Table 3
Life Cycle Inventory of 1 m³ of SHLC⁴ formulations.

Flow	SHLC4-50	SHLC4-35	SHLC4-25	Unit	Process	Data Source
CEM I 52.5	586	405	287	kg/m ³	Cement (CEM I 52.5), Portland cement	Sphera, DE
Calcined Clay	376	491	565	kg/m ³	Calcined clay production	Ecoinvent 3.8, RoW (1)
Limestone	188	246	283	kg/m ³	Limestone flour (20 μm)	Sphera, DE
Gypsum	18	12	9	kg/m ³	Gypsum plaster (CaSO ₄ beta hemihydrate)	Sphera, DE
Superplasticizer	4	5	6	kg/m ³	Concrete admixtures (superplasticizer)	EPD (2), DE
VMA	4	4	4	kg/m ³	Concrete admixtures (water-retaining)	EPD (2), DE
Water	468	463	459	kg/m ³	Tap water from groundwater	Sphera, DE
Quartz Sand	263	260	257	kg/m ³	Dried quartz sand, grain size 0/2	Sphera, DE
PE fibers	20	20	20	kg/m ³	Polyethylene fibers (HDPE/PE-HD)	Sphera, DE
PP fibers	23	23	23	kg/m ³	Polypropylene fibers (PP)	Sphera, RER (3)
PET fibers	34	34	34	kg/m ³	Polyethylene terephthalate fibers (PET)	Sphera, DE

(1) RoW: Rest of the World.
(2) EPD from Deutsche Bauchemie (DBC).
(3) RER: Europe.

hoc, we base our monetary valuation on the LCSC framework proposed by Huang et al. (2025), which was developed specifically for LC³ concretes under a cradle-to-gate scope and relies on a coherent set of WTP-based MVCs for the same CML impact categories considered in this study.

In our case, we build on the LCSC model, adapting it to the German context and updating values to a 2025 reference year. The LCSC integrates two components in Eq. (1): (i) the procurement costs of raw materials, reflecting real market expenditures, and (ii) the monetized environmental impacts, based on life cycle emissions and corresponding MVCs, thereby expressing economic and environmental aspects in a common monetary metric.

$$LCSC = \sum_{j=1}^n c_j \cdot M_j + \sum_{i=1}^4 EF_i \cdot MVC_i \quad (1)$$

where:

LCSC : life cycle sustainable cost;

c_j : unit cost of material j [€/kg or €/m³];

M_j : quantity of material j used per functional unit;

n : total number of distinct materials;

EF_i : environmental footprint for impact category i ;

MVC_i : monetary valuation coefficient for impact category i [€/unit of impact];

$i = 1, \dots, 4$ corresponding to GWP, AP, EP, and POCP.

Material procurement costs (in €/kg) are presented in Table 4. Cost collection followed a source hierarchy: (i) laboratory procurement records, (ii) supplier quotations, and (iii) proxy values from literature. The latter was only used in cases where manufacturers did not disclose pricing information despite direct requests, such as for calcined clay and PET fibers. For calcined clay, the unit price reported by Kanagaraj et al. (2024) was adopted as the most recent and representative reference. For PET fibers, we referred to Kumar and Rai (2023), who reported the cost of Recron polyester fibers with physical and mechanical properties comparable to those used in the present work. All costs were inflation-adjusted and converted to euros. While the use of diverse cost sources adds complexity to the data, acknowledging this variation and carefully assessing each source supports a more informed interpretation of the economic findings.

As the monetary valuation of LC³-based concretes is not yet common in the literature, the MVCs used in this study (see Table 5) were selected for their methodological alignment with the German building sector, rather than strict contextual similarity. Specifically, the factors are based on the comprehensive review by Schneider-Marín and Lang (2020), which provides regionally appropriate, peer-reviewed monetary conversion factors for key LCA impact categories, namely

Table 4

Material procurement costs used for LCSC calculation. Unit prices are based on supplier quotes or laboratory records.

Material	Unit Price (€/kg)	Source
Cement	0.20	Supplier
Calcined Clay	0.10 ^a	Kanagaraj et al. (2024)
Limestone	0.50	Laboratory
Gypsum	17.33	Laboratory
Quartz Sand	0.06 ^b	Supplier
Superplasticizer	3.85	Laboratory
VMA	10.00	Supplier
PE Fibers	49.50	Laboratory
PP Fibers	2.50	Supplier
PET Fibers	3.99 ^a	Kumar and Rai (2023)

^a Adjusted for 2025 and converted to €.

^b Mid-point of supplier's kiln-dried 60–200 μm quartz-sand quote (35–85 €/t); taken as representative price for the study.

GWP, AP, EP, and POCP — commonly reported for cement production and polymer fiber manufacturing. These categories also represent the midpoint indicators for which reliable monetary valuation data and consistent methodological guidance are available in the European context (Pizzol et al., 2015).

To ensure temporal comparability, all monetary values — including direct material costs from the literature and monetized environmental impacts — were adjusted for inflation using the Consumer Price Index (CPI) (Amadei et al., 2021). Values were converted to the 2025 reference year to account for changes in purchasing power over time. The adjustment of MVCs for inflation is performed using Eq. (2).

$$Final\ Value_{2025} = Present\ Value_j \times \frac{CPI_{2025}}{CPI_j} \quad (2)$$

where:

Final Value₂₀₂₅ : monetary value expressed in 2025 currency;

Present Value _{j} : original monetary value reported for year j ;

CPI₂₀₂₅ : Consumer Price Index in the year 2025;

CPI _{j} : Consumer Price Index in the original reporting year j .

Source: Amadei et al. (2021).

The final LCSC for each composite variation is determined by summing the material cost and the inflation-adjusted monetary environmental costs.

5. Results and discussion

5.1. Life cycle assessment of SHLC⁴ composites

As previously outlined, a LCA was conducted on seven SHLC⁴ composite formulations. These varied by three levels of clinker replacement

Table 5

Adapted monetary valuation coefficients of mid-point indicators (reference year: 2025). Includes minimum and maximum values, methods used, and respective sources.

Indicator	Unit	Min (€)	Method	Max (€)	Method	Sources (Min–Max)
GWP	kg CO ₂ -eq.	0.03	Abatement cost	0.84	Damage cost	atmosfair gGmbH (2019) – Matthey and Bünger (2019)
AP	kg SO ₂ -eq.	2.29	Damage cost	19.42	Damage cost	Adensam et al. (2002) – Bünger and Matthey (2018), Matthey and Bünger (2019)
POCP	kg C ₂ H ₄ -eq.	0.36	Damage cost	12.94	Averting behavior	Adensam et al. (2002) – Vogtländer (2016)
EP	kg PO ₄ ³⁻ -eq.	2.30	Damage cost	23.91	Damage cost (WTP)	Adensam et al. (2002) – Ahlroth (2009)

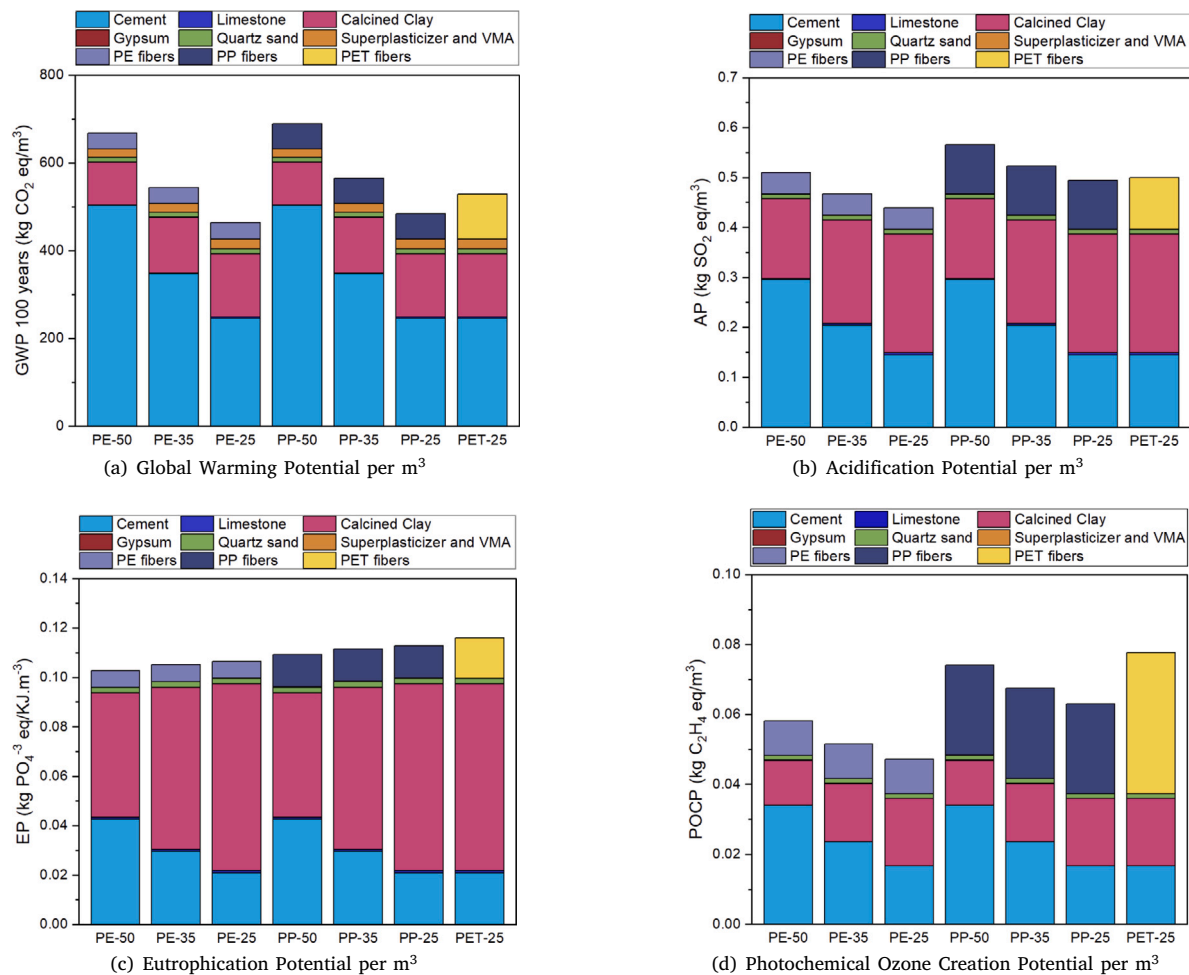


Fig. 2. Impact assessment per cubic meter of composite for different SHLC⁴ formulations.

(25%, 35%, and 50%) and three types of synthetic fibers: PP, PE, and PET. Due to concerns regarding PET fiber degradation (discussed in Section 2.1), the 25%-PET formulation featuring mild alkalinity was the only mix evaluated for PET fibers.

Environmental impacts were calculated using the mid-point indicators from the CML 2001 method (Guinée, 2001). Results are first reported per unit volume (1 m³ of composite), then by the composites’ work-to-fracture (energy absorption capacity), in order to evaluate the environmental efficiency of the composites per unit toughness. As noted in Section 3.4, the available LCA dataset for PE fibers may notably underestimate the actual environmental burden associated with the production of high- and ultra-high-molecular weight PE fibers used in high-performance protective composites (Bracklow et al., 2025), so the PE-based results should be interpreted with that limitation in mind.

5.1.1. Results per cubic meter

Fig. 2 presents the environmental impacts per cubic meter of composite for all four categories.

For GWP, as anticipated, the OPC component (CEM I 52.5) is the dominant contributor in all SHLC⁴ formulations. In high-binder mixes (50%), OPC alone contributes over 500 kg CO₂-eq/m³, accounting for roughly 73% of total GWP due to the energy- and fuel-intensive clinkering process. Reducing clinker content to 25% cuts emissions by nearly a third in PE-25 and PP-25, which highlights the significant climate impact of cement reductions in high-performance cementitious composites. Calcined clay, although a lower-carbon alternative to OPC, still represents a relevant share of total GWP in low-clinker mixes (e.g. about 144 kg CO₂-eq/m³, or just over 30% of total GWP in PE-25), whereas limestone makes only a negligible contribution (around 2 kg CO₂-eq/m³), confirming its suitability as a low-impact filler in LC³ systems.

Among the three fiber types assessed, PET has the highest per-tonne GWP (2985.9 kg CO₂-eq/t), followed by PP (2494.1 kg CO₂-eq/t) and PE (1832.9 kg CO₂-eq/t). When combined with their respective dosages, this results in fiber-related contributions of about 101.5 kg CO₂-eq/m³ in PET-25, 57.4 kg CO₂-eq/m³ in PP-based mixes,

and 36.7 kg CO₂-eq/m³ in PE formulations. Overall, PE-25 exhibits the lowest GWP per m³ among all formulations (463.4 kg CO₂-eq/m³), whereas PP-50 shows the highest value (689.0 kg CO₂-eq/m³) because of the combined effect of high OPC content and PP fibers.

Regarding AP, expressed in kg SO₂-equivalent, the values range from 0.482 kg SO₂-eq/m³ for the less impactful combination (PE-25) to 0.603 kg SO₂-eq/m³ for the most impactful counterpart (PP-50). Similarly to the GWP trend, OPC content remains the dominant contributor, accounting for 49%–54% of total AP in high-binder (50%) scenarios. Calcined clay is a secondary driver, particularly in low-clinker systems, accounting for nearly 50% of total of PE-25. Fiber selection also affects AP outcomes. PP exhibits the greatest AP per ton (4.26 kg SO₂-eq/t), an indication of its more energy-intensive production.

When it comes to EP, reported in kg PO₄³⁻-eq/m³, the SHLC⁴ mixes show relatively small variations, from 0.110 kg PO₄³⁻-eq/m³ for PE-50 to 0.125 kg PO₄³⁻-eq/m³ for PET-25. Calcined clay is the principal contributor across all scenarios: its EP factor (0.134 kg PO₄³⁻-eq/t) is nearly twice that of cement (0.073 kg PO₄³⁻-eq/t), and it accounts for roughly 43%–65% of total EP in both high- and low-binder formulations. Fiber choice further modulates EP: PET and PP exhibit relatively high EP factors (0.48 and 0.57 kg PO₄³⁻-eq/t, respectively), amplifying impacts in PET-25 and PP-based mixes, whereas the lower factor of PE (0.34 kg PO₄³⁻-eq/t) contributes to the comparatively low EP of PE-50.

For POCP, expressed in kg C₂H₄-eq/m³, values range from 0.051 kg C₂H₄-eq/m³ in PE-25 to 0.082 kg C₂H₄-eq/m³ in PET-25. Here, fiber selection plays a disproportionately large role compared to the other impact categories. In SHLC⁴-50 mixes, cement is still the main contributor (about 44%–55% of total POCP) due to NO_x and hydrocarbon emissions from kiln processes, but its influence decreases markedly as clinker content is reduced. In PP-25 and PET-25, PP and PET fibers, despite representing only 2.5% by volume, contribute more to POCP than either binder component: with POCP factors of 1.12 and 1.19 kg C₂H₄-eq/t, respectively, they account for over 38% of total POCP in PP-25 and nearly 50% in PET-25. Admixtures (VMA and superplasticizer) contribute consistently across all mixes (around 5%–8%), despite their low dosages.

5.1.2. Results per work-to-fracture (kJ/m³)

The specific environmental impacts of SHLC⁴ in relation to their mechanical performance are most relevant to our investigation scenario. The four impact categories are shown in Fig. 3, expressed relative to the corresponding work-to-fracture of each composite formulation. When these results are expressed relative to the mechanical performance, a clear and consistent pattern emerges: PP-reinforced concretes with higher binder contents (–50 and –35 mixes) exhibit the highest environmental burdens. This is primarily due to their low mechanical performance (39.5–60.2 kJ/m³), which amplifies impacts when assessed per functional unit. In fact, lower mechanical performance leads to higher material depletion to meet the design requirements. Moreover, PP is the most environmentally intensive fiber concerning acidification and eutrophication, with emission factors of 4.26 kg SO₂-eq/t and 0.57 kg PO₄³⁻-eq/t, respectively. While its contributions to GWP and POCP are moderate, the combination of elevated emissions in key categories and limited fracture energy turns PP-based mixes environmentally inefficient. Many viable strategies have been investigated to improve the toughness of SHCC with PP fibers, thereby making them attractive for a variety of structural applications, including industrial pavements and structural strengthening and protection (Signorini et al., 2022).

Although PE-25 shows only moderate impacts when considered per unit weight, it performs poorly when normalized to energy absorption due to its relatively low fracture energy (69.6 kJ/m³), a result of the significant mismatch between matrix and fibers (Ahmed et al., 2024b). Interestingly, at the opposite end of the spectrum, PE-50 delivers the lowest impact per energy absorbed in three out of four categories,

closely followed by PET-25, which ranks lowest in GWP and second in AP and EP, despite a mid-range POCP. PE-50 benefits from the highest fracture energy (142.3 kJ/m³), which compensates for its high binder content. PET-25, in contrast, combines relatively high fracture energy (125.6 kJ/m³) with a lower binder content, thereby moderating the contribution from its more carbon-intensive fiber. These two formulations represent the two extremes of mix design concepts. PE-35 consistently falls in between, balancing cement content and fiber type for mid-range W_f and impacts.

Overall, the results indicate that fracture energy exerts a strong influence on environmental impact results, and its consideration in LCA is crucial for objective and efficient decision-making. Additionally, the significant potential for recycling PP and PET fibers, especially PET (Signorini and Nobili, 2022), could create promising opportunities in sustainable composite design.

5.2. Monetary valuation

5.2.1. Material costs

As shown in Table 4, the procurement costs of individual materials vary significantly depending on their composition, processing method, and specificity. For instance, since a high-purity gypsum was used, it resulted in a notably high unit cost compared to industrial-grade alternatives. The most prominent cost driver, however, is UHMWPE fibers (Dyneema®), which reflects the energy- and solvent-intensive gel-spinning process required to produce the alignment of the molecular chains and high crystallinity, thereby enabling efficient force transfer along the fiber backbone as advocated by high-performance standards. In contrast, PET and PP fibers are produced via melt-spinning, an energy-efficient process that avoids solvent use. These fibers can be up to 95% cheaper than UHMWPE alternatives in Europe, as reported by Liao et al. (2024).

Fig. 4 illustrates the total material procurement costs per cubic meter for each SHLC⁴ formulation and breaks down the contributions by individual materials. The type and dosage of fibers, particularly the use of UHMWPE, as well as the binder, are shown to significantly influence the overall cost structure across formulations. This observation is consistent with the findings of Li et al. (2022), whose SHCC formulations incorporating PVA and basalt fibers exceeded \$800/m³ in materials cost, roughly four times that of conventional concrete, primarily due to the high fiber content.

Due to the significant impact of fiber prices, particularly UHMWPE, on the overall cost structure, we performed a sensitivity analysis, simulating a ±20% variation in fiber unit prices across two scenarios: all fibers and PE only (see Tables A.8 and A.9 in the Appendix, respectively). While the absolute costs varied accordingly, the relative cost ranking of the formulations remained unchanged, suggesting that the comparative findings are robust to reasonable fluctuations in fiber pricing.

When comparing formulations based solely on binder composition instead, it becomes clear that mixes with higher clinker factors are inherently more expensive, as cement is twice as expensive as calcined clay. Using industrial-grade gypsum, rather than high-purity laboratory grades, can further minimize costs, particularly in large-scale production scenarios. As for fibers, PP-based mixes are the most economical choices. PET is about 1.5 times more costly, while UHMWPE is nearly 20 times more expensive than PP. Therefore, higher clinker contents, high-purity additives, and UHMWPE fibers significantly increase total costs, while lower-clinker binders, industrial-grade gypsum, and PET/PP fibers provide more economical alternatives.

5.2.2. Environmental costs

To estimate the environmental externalities of all SHLC⁴ formulations, we applied the MVCs in Table 5, updated to 2025 values. These coefficients, originally compiled by Schneider-Marín and Lang (2020), provide minimum–maximum ranges derived from different

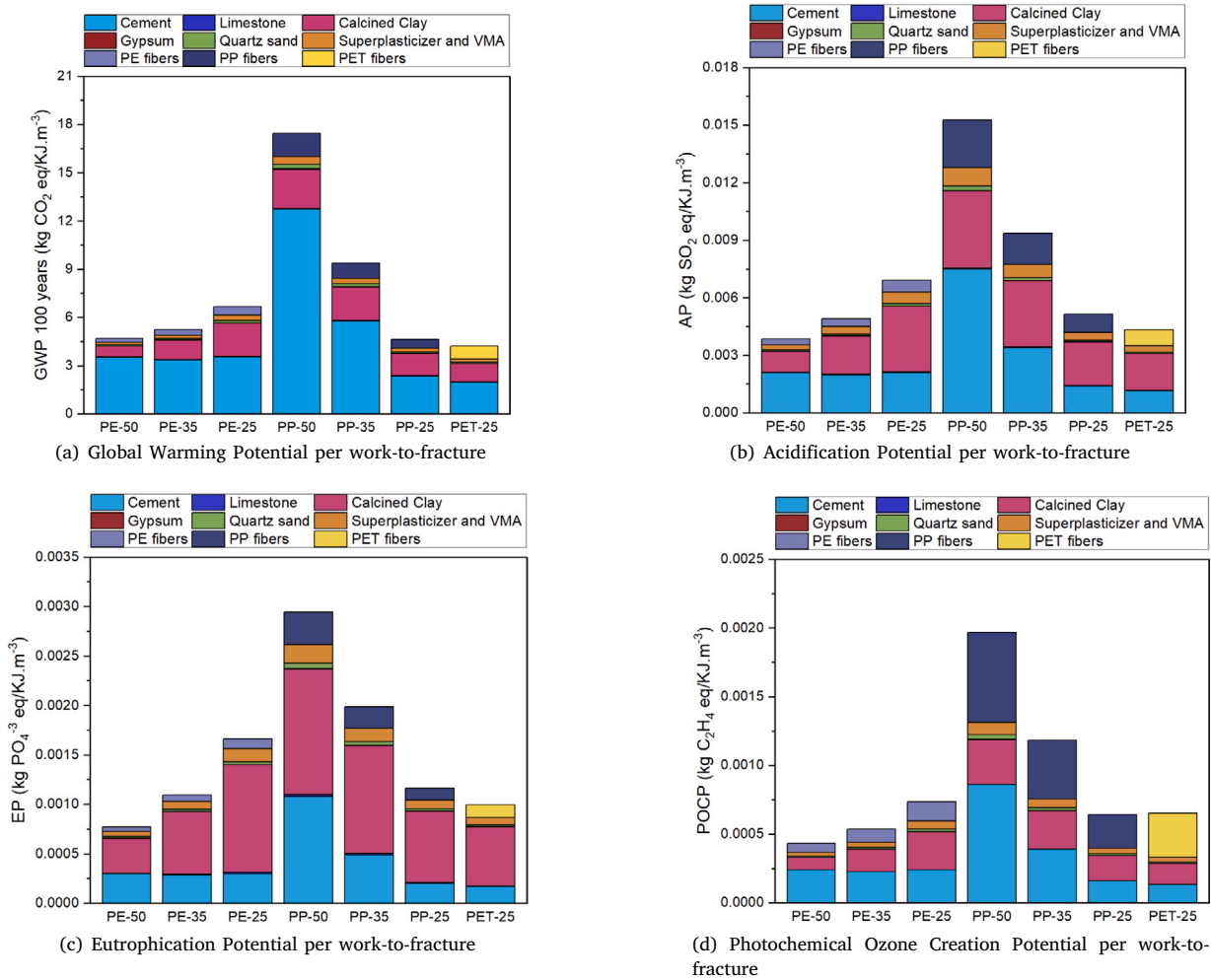


Fig. 3. Impact assessment per unit work-to-fracture for different SHLC⁴ formulations.

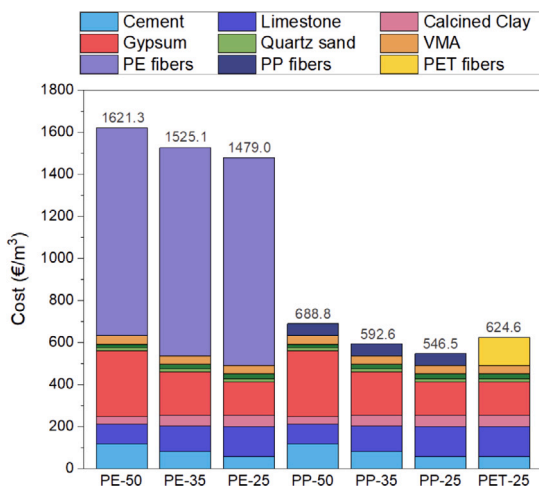


Fig. 4. Material cost breakdown per m³ for each SHLC⁴ formulation.

valuation methodologies, capturing the uncertainty across impact categories. Environmental costs were calculated for the two functional units identified previously, i.e. per cubic meter (Table 6) and per work-to-fracture (Table 7).

For the minimum MVC values, the environmental costs were almost negligible, particularly when compared to the high direct material costs. However, assuming the upper valuation boundaries, the external cost share rises substantially. For instance, the PET-25 mix, with moderate fiber cost, reaches an external cost of up to €443.25/m³ under the highest GWP valuation, compared to a direct material cost of approximately €624.60. This suggests that under high damage-cost assumptions, even relatively affordable formulations can have nearly half of their life-cycle cost attributable to environmental burdens.

The relative cost-efficiency of the formulations depends on the functional unit applied. When environmental costs are calculated per cubic meter, PE-50 and PP-50 are the most expensive formulations, mainly due to their high Portland cement content and the associated GWP emissions. PE-25 is the most cost-efficient on a volume basis, benefiting from reduced cement content and the use of the least GWP-intensive fiber. When costs are expressed per work-to-fracture to provide a performance-based perspective, PET-25 becomes the most cost-effective mix, pairing moderate environmental impacts with good toughness. PE-50 and PP-25 also gain relative competitiveness under this metric. In both minimum and maximum valuation scenarios, however, PP-50 remains the least cost-effective option, with W_j -based costs two to four times higher than those of other mixes, due to its poor mechanical performance.

When it comes to the relative contribution of impact categories to total externalities (as illustrated in Fig. 5), results are consistent across both functional units. In all cases, GWP overwhelmingly dominates

Table 6
Monetized environmental costs per cubic meter of SHLC⁴ formulations.

SHLC ⁴	GWP (€/m ³) min-max	AP (€/m ³) min-max	EP (€/m ³) min-max	POCP (€/m ³) min-max
PE-50	17.26–560.81	1.25–10.63	0.25–2.63	0.02–0.80
PE-35	14.05–456.48	1.16–9.85	0.26–2.71	0.02–0.71
PE-25	11.96–388.82	1.10–9.35	0.27–2.77	0.02–0.66
PP-50	17.79–578.19	1.38–11.70	0.27–2.78	0.03–1.00
PP-35	14.58–473.85	1.29–10.92	0.27–2.86	0.03–0.92
PP-25	12.50–406.20	1.23–10.42	0.28–2.91	0.02–0.87
PET-25	13.64–443.25	1.24–10.54	0.29–2.99	0.03–1.06

Table 7
Monetized environmental costs per unit of work-to-fracture for SHLC⁴ formulations.

SHLC ⁴	GWP (€/kJ) min-max	AP (€/kJ) min-max	EP (€/kJ) min-max	POCP (€/kJ) min-max
PE-50	0.12–3.94	0.009–0.075	1.78E–03–1.85E–02	1.57E–04–5.61E–03
PE-35	0.14–4.41	0.011–0.095	2.51E–03–2.62E–02	1.93E–04–6.90E–03
PE-25	0.17–5.59	0.016–0.134	3.82E–03–3.97E–02	2.65E–04–9.50E–03
PP-50	0.45–14.64	0.035–0.296	6.77E–03–7.04E–02	7.10E–04–2.54E–02
PP-35	0.24–7.87	0.021–0.181	4.56E–03–4.75E–02	4.27E–04–1.53E–02
PP-25	0.12–3.88	0.012–0.100	2.68E–03–2.79E–02	2.32E–04–8.29E–03
PET-25	0.11–3.53	0.010–0.084	2.29E–03–2.38E–02	2.35E–04–8.41E–03



Fig. 5. Relative contribution of external (environmental) costs per impact category for each SHLC⁴ formulation under the maximum valuation scenario.

the environmental cost profile, regardless of the mix, accounting for 96.62% (PP-25) to 97.55% (PE-50) of the total. This dominance is not due to GWP's cost; in fact, its valuation is significantly lower (€0.84/kg CO₂-eq at most) than that of acidification (€19.42/kg SO₂-eq), eutrophication (€23.91/kg PO₄³⁻-eq), or POCP (€12.94/kg C₂H₄-eq). The severe economic impact of GWP rather reflects the remarkable absolute quantity of CO₂-equivalent emissions associated with the cement-rich binder content of SHCC formulations.

5.2.3. Total life cycle sustainability costs

The total LCSC is calculated as the sum of direct material procurement costs and the monetized environmental externalities. Fig. 6 presents the total LCSC under the maximum valuation scenario normalized by two distinct functional units. When expressed per cubic meter (Fig. 6(a)), LCSC ranges from approximately €966.9 for PP-25 to €2196.2 for PE-50, the latter being heavily influenced by the high cost of UHMWPE fibers. As discussed earlier, under minimum valuation assumptions, environmental externalities are virtually negligible—contributing less than 2.0% to LCSC, leaving material costs as the

dominant driver Appendix B. However, in the maximum valuation scenario, the cost distribution becomes more balanced: environmental externalities account for 21.4–46.3% of total LCSC, depending on the formulation. Notably, this shift is most pronounced in PP-based and PET-based formulations, where externalities represent nearly half the total cost. The main exception remains the PE-based mixes, where high fiber prices dominate the overall cost structure, leaving environmental costs with a relatively smaller share.

When expressed in relation to work-to-fracture (Fig. 6(b)), the pattern between direct and external costs persists: environmental externalities account for 29%–46% of total LCSC depending on the mix. This impact share remains lower in PE-based formulations due to the dominant influence of UHMWPE fiber prices, but is particularly pronounced in PP- and PET-based mixes, where environmental costs approach or exceed 40% of the total. The cost hierarchy between the formulations, however, changes. PET-25 is the most cost-efficient (€8.62/kJ), closely followed by PP-25 (€9.24/kJ). In contrast, PP-50, penalized by its low fracture energy, becomes the most expensive at €32.47/kJ — almost four times higher than PET-25. The PE mixes show variable results: PE-50 benefits from its very high fracture energy, lowering its cost to €15.43/kJ, while PE-25 performs poorly (€27.02/kJ) due to reduced toughness at lower clinker content.

Additionally, it is important to remember that the environmental impact of PE fibers is underestimated because the database information pertains to standard PE, which involves less energy-intensive processes. This makes alternative options, such as PET and PP fibers, even more attractive in terms of cost-effectiveness. For high-performance applications, however, a trade-off must be identified because UHMWPE fibers combined with high-strength cementitious matrices represent the highest-performing internal reinforcement among the options presented here.

5.3. Trade-offs between environmental, economic, and mechanical performance

To consolidate and represent the multi-dimensional performance of each SHLC⁴ mix, Fig. 7 presents a heat-map of four normalized indicators: GWP (environmental impact), work-to-fracture (mechanical performance), and both external and direct material costs. All values were scaled using min-max normalization, where 0 indicates best performance and 1 the worst. For work-to-fracture, the direction was inverted so that higher toughness yields better (lower) scores.

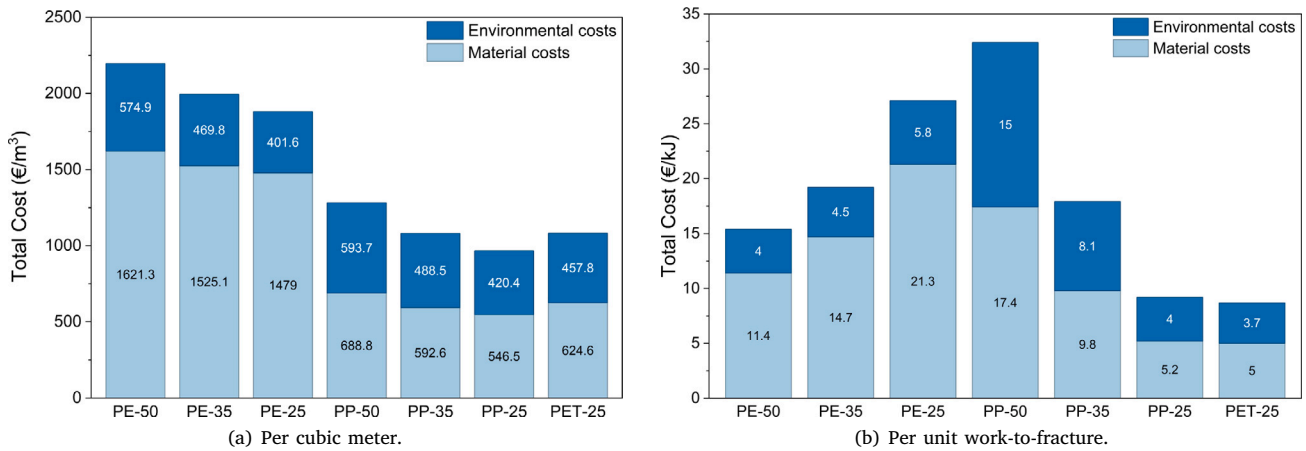


Fig. 6. Total life-cycle sustainable cost (LCSC) per functional unit under the maximum valuation scenario, combining direct material and environmental costs.

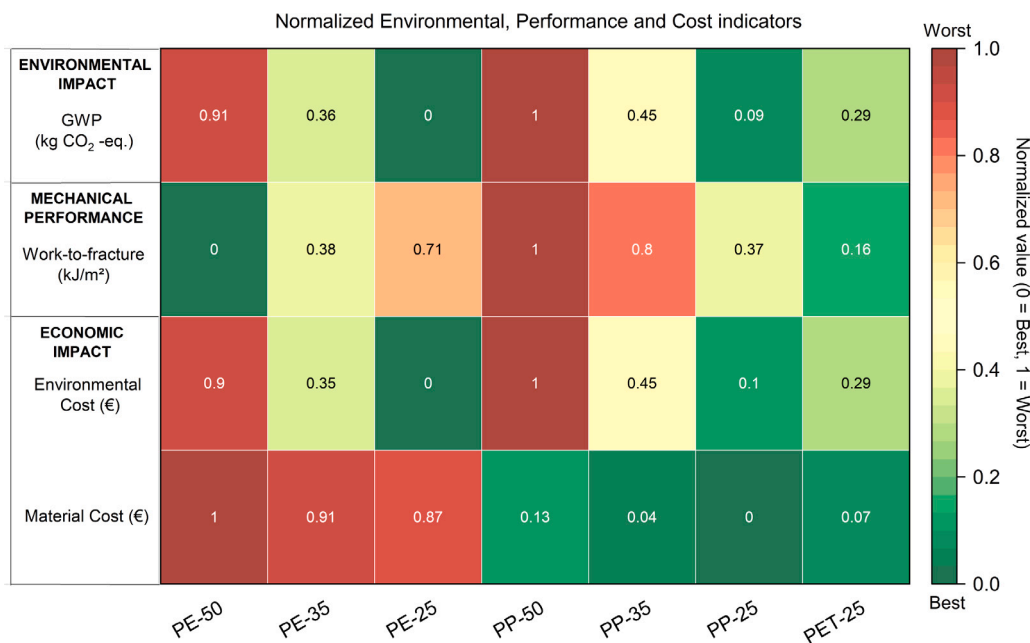


Fig. 7. Normalized sustainability heat-map comparing the relative performance of SHLC⁴ formulations in the dimensions Environmental Impact (GWP₁₀₀), Economic Impact (material and environmental/external cost), and Mechanical Performance (work-to-fracture). Lower values indicate better performance in each metric. The range from “0 = Best” (green) to “1 = Worst” (red) is applied horizontally, within dimensions, not throughout the entire chart.

Although the LCA included four environmental impact categories, GWP was used here as the representative metric, as it reflects both its dominance in external cost calculations and its particular relevance to concrete systems due to its link with cement-related emissions. Including all categories would unnecessarily complicate visualization without significantly altering the outcomes. Additionally, to ensure consistent comparison, all indicators were calculated per cubic meter of composite.

In consideration of the purely scientific and methodological character of this study, it was deliberately decided to eschew the quantification of each of the categories (i.e., environmental, mechanical, economic) and instead to present them separately. Applying weights would require making explicit assumptions about the relative value of environmental, economic, and performance indicators. Previous studies have shown that weighting choices can easily become subjective and significantly impact the outcome (Schultze and Trommer, 2012).

As the matrix illustrates, no single mix outperforms across all dimensions. PE-50 achieves the highest mechanical efficiency but remains

the least cost-effective option due to its high fiber price. PP-50, on the other hand, scores poorly on all metrics, with low toughness and high environmental and financial burdens. In contrast, PET-25 and PP-25 exhibit the most balanced trade-offs, offering moderate environmental impacts, acceptable performance, and competitive costs. PE-25 and PE-35 occupy an intermediate space, with good environmental profiles but limited cost-efficiency due to fiber pricing.

6. Conclusions and outlook

This study evaluated the life-cycle performance of seven strain-hardening limestone calcined clay cement composite (SHLC⁴) formulations, combining varying levels of clinker replacement with three types of synthetic fibers. By integrating life cycle assessment (LCA), life cycle sustainable cost (LCSC), and mechanical performance metrics, a comprehensive sustainability profile was established for each mix.

The findings demonstrate clear trade-offs between environmental impact, cost, and mechanical performance:

- High mechanical performance does not imply sustainability. PE-50 achieved the highest work-to-fracture values due to the exceptional toughness of UHMWPE fibers. However, its excessively high cost — driven by fiber price — rendered it the least cost-efficient formulation, even when normalized by impact absorption.
- SHLC⁴ that combines UHMWPE fibers and high-cement binders (e.g., PE-50) may be viable for special case scenarios where their exceptional mechanical properties are needed to meet specific design requirements and where material depletion can be minimized and optimized (e.g., retrofitting and protecting structures with thin, externally bonded layers).
- PP-50 underperformed across the board. It exhibited the highest environmental burdens, lowest mechanical performance, and high overall costs. As such, it was the least favorable mix in both functional and economic terms.
- PET-25 and PP-25 offer the best overall balance. PET-25 combined high fracture energy with moderate environmental and economic impacts, while PP-25 was the most affordable option, albeit with lower toughness. Both emerged as the most sustainable formulations when all performance dimensions were considered jointly.
- Using highly recyclable fibers obtained from abundant industrial and consumer waste (PET in particular) can significantly improve the environmental and financial viability of SHLC⁴.
- Intermediate mixes presented nuanced trade-offs. PE-35 and PE-25 offered moderate performance and relatively low environmental impacts, yet remained economically noncompetitive due to UHMWPE cost. Interestingly, work-to-fracture declined with clinker content in PE-based mixes, but improved in PP-based ones—highlighting the role of matrix–fiber compatibility in mechanical efficiency.

Overall, the results demonstrate that superior SHCC performance can be achieved without relying on high-impact constituents. Mixes that incorporate low-clinker binders and conventional polymeric fibers delivered competitive mechanical properties, as well as measurable environmental and economic benefits, which highlights the feasibility of designing resilient, lower-carbon cement composites that balance work-to-fracture, cost, and sustainability. The favorable performance of the PET-25 formulation, in particular, should be interpreted in the context of low-alkalinity LC³-25 matrices, which significantly mitigate PET degradation and enable adequate fiber–matrix compatibility both in the short and long term.

The study also provides a methodology that combines performance-based functional units, life cycle assessment, and life cycle sustainable cost, offering a structured framework for optimizing future materials and infrastructure developments with respect to both mechanical performance and environmental–economic trade-offs.

Future work should expand upon the current cradle-to-gate assessment by explicitly modeling end-of-life scenarios for LC³-based SHCC, integrating realistic recycling and disposal pathways, as well as their environmental implications. Additionally, although durability lies beyond the scope of the present cradle-to-gate analysis, we acknowledge that long-term performance and resistance to environmental exposure can vary across LC³-based SHCC due to matrix–fiber interactions, matrix alkalinity, and exposure conditions, potentially influencing both functional performance and sustainability. Accordingly, it should move beyond the simplifying assumption of equal durability across analyzed composites by quantifying service life under different exposure conditions and integrating this information into performance-based functional units and associated life cycle indicators.

Table A.8Sensitivity analysis by comparing the reference vs. $\pm 20\%$ cost variation for all fibers.

Mix	Reference (€)	+20% all fibers (€)	–20% all fibers (€)
PP-25	546.48	557.98	534.98
PP-35	592.62	604.12	581.12
PET-25	624.64	651.78	597.51
PP-50	688.82	700.32	677.32
PE-25	1478.98	1676.98	1280.98
PE-35	1525.12	1723.12	1327.12
PE-50	1621.32	1819.32	1423.32

Table A.9Sensitivity analysis by comparing the reference vs. $\pm 20\%$ cost variation for PE only.

Mix	Reference (€)	+20% PE only (€)	–20% PE only (€)
PP-25	546.48	546.48	546.48
PP-35	592.62	592.62	592.62
PET-25	624.64	624.64	624.64
PP-50	688.82	688.82	688.82
PE-25	1478.98	1676.98	1280.98
PE-35	1525.12	1723.12	1327.12
PE-50	1621.32	1819.32	1423.32

CRedit authorship contribution statement

Isabela de Paula Salgado: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ameer Hamza Ahmed:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Tobias Hatzfeld:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Cesare Signorini:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization. **Edeltraud Guenther:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition. **Viktor Mechtcherine:** Writing – review & editing, Supervision, Resources, Funding acquisition.

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Declaration of competing interest

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

Appendix A. Sensitivity analysis for cost variability

To assess the impact of pricing of fibers in the economic valuation, a one-factor sensitivity analysis at $\pm 20\%$ was performed. Tables A.8 and A.9 respectively report a simultaneous $\pm 20\%$ change to all fiber unit prices (PE, PP, and PET), and a $\pm 20\%$ change to PE only, while holding PP and PET constant. Material costs are expressed per m³ of composite.

Table B.10Material, environmental, and life cycle sustainability costs (LCSC) per cubic meter for SHLC⁴ formulations.

SHLC ⁴	Min Costs (€/m ³)			Max Costs(€/m ³)		
	Material	Environmental	LCSC	Direct	Environmental	LCSC
PE-50	1621.30	18.78	1640.10	1621.32	574.87	2196.19
PE-35	1525.10	15.49	1540.60	1525.12	469.75	1994.88
PE-25	1479.00	13.35	1492.30	1478.98	401.60	1880.59
PP-50	688.80	19.46	708.30	688.82	593.67	1282.49
PP-35	592.60	16.17	608.80	592.62	488.55	1081.18
PP-25	546.50	14.03	560.50	546.48	420.40	966.89
PET-25	624.60	15.20	639.80	624.64	457.84	1082.49

Table B.11Material, environmental, and life cycle sustainability costs (LCSC) per unit of work-to-fracture for SHLC⁴ formulations.

SHLC ⁴	Min Costs (€/kJ)			Max Costs (€/kJ)		
	Material	Environmental	LCSC	Material	Environmental	LCSC
PE-50	11.40	0.13	11.50	11.39	4.04	15.43
PE-35	14.70	0.15	14.90	14.72	4.53	19.26
PE-25	21.20	0.19	21.40	21.25	5.77	27.02
PP-50	17.40	0.49	17.90	17.44	15.03	32.47
PP-35	9.80	0.27	10.10	9.84	8.12	17.96
PP-25	5.20	0.13	5.40	5.22	4.02	9.24
PET-25	5.00	0.12	5.10	4.97	3.65	8.62

Appendix B. Life cycle sustainability costs

See Tables B.10 and B.11.

Data availability

Data will be made available on request.

References

- Adensam, H., Bruck, M., Geissler, S., Fellner, M., 2002. Externe Kosten im Hochbau. Band I. n.p., Wien.
- ADVANSANSA, 2020. The fact sheet was obtained directly from the company. ADVANSANSA Manufacturing GmbH (2020) PET (polyethylene terephthalate) short-cut fibres. Product specification/certificate of conformance.
- Ahlroth, S., 2009. Valuation of Environmental Impacts and its Use in Environmental Systems Analysis Tools (Ph.D. thesis). Royal Institute of Technology, Stockholm.
- Ahmed, A.H., Hübner, J., Junger, D., Signorini, C., Butler, M., Liebscher, M., Scheffler, C., Mechtcherine, V., 2025. Engineering low clinker strain-hardening cementitious composites (SHCC) using polyethylene and cost-effective polypropylene fibers: An experimental scale-linking analysis. *Mater. Des.* 114051. <http://dx.doi.org/10.1016/j.matdes.2025.114051>.
- Ahmed, A.H., Liebscher, M., Signorini, C., Mechtcherine, V., 2024a. Investigating the potential of limestone and calcined clay as a substitute for fly ash in strain-hardening cementitious composites (SHCC). *Spec. Publ.* 362, 321–330. <http://dx.doi.org/10.14359/51740893>.
- Ahmed, A.H., Nune, S., Liebscher, M., Köberle, T., Willomitzer, A., Noack, I., Butler, M., Mechtcherine, V., 2023. Exploring the role of dilutive effects on microstructural development and hydration kinetics of limestone calcined clay cement (LC³) made of low-grade raw materials. *J. Clean. Prod.* 428, 139438. <http://dx.doi.org/10.1016/j.jclepro.2023.139438>.
- Ahmed, A.H., Signorini, C., Chikhradze, M., Liebscher, M., Butler, M., Mechtcherine, V., 2024b. Employing limestone and calcined clay for preserving the strain-hardening response of PET fiber-reinforced cementitious composites. *Constr. Build. Mater.* 438, 137166. <http://dx.doi.org/10.1016/j.conbuildmat.2024.137166>.
- Amadei, A.M., De Laurentiis, V., Sala, S., 2021. A review of monetary valuation in life cycle assessment: State of the art and future needs. *J. Clean. Prod.* 329, 129668. <http://dx.doi.org/10.1016/j.jclepro.2021.129668>.
- atmosfair gGmbH, 2019. FAQs Zur CO₂-Berechnung. Technical Report, atmosfair gGmbH, URL https://www.atmosfair.de/de/faqs/zur_co2_berechnung/. (Accessed 26 May 2025).
- Bracklow, F., Jackson, C.M., Signorini, C., Jacques, E., Beckmann, B., Curbach, M., Mechtcherine, V., 2025. Hybrid mineral-bonded protective layers for enhanced self-centering capacity of reinforced concrete beams subjected to blast. *Eng. Struct.* 322, 119151. <http://dx.doi.org/10.1016/j.engstruct.2024.119151>.
- Brouwer, F., Caucci, S., Karthe, D., Kirschke, S., Madani, K., Mueller, A., Zhang, L., Guenther, E., 2023. Advancing the resource nexus concept for research and practice. In: *Sustainability Nexus Forum*, vol. 31, (1), Springer, pp. 41–65. <http://dx.doi.org/10.1007/s00550-024-00533-1>.
- Bünger, B., Matthey, A., 2018. *Methodenkonvention 3.0 zur Ermittlung von Umweltkosten: Methodische Grundlagen*. Technical Report, Umweltbundesamt, Dessau-Roßlau.
- Chiaia, B., Fantilli, A.P., Guerini, A., Volpatti, G., Zampini, D., 2014. Eco-mechanical index for structural concrete. *Constr. Build. Mater.* 67, 386–392. <http://dx.doi.org/10.1016/j.conbuildmat.2013.12.090>.
- Curosu, I., Mechtcherine, V., Forni, D., Cadoni, E., 2017. Performance of various strain-hardening cement-based composites (SHCC) subject to uniaxial impact tensile loading. *Cem. Concr. Res.* 102, 16–28. <http://dx.doi.org/10.1016/j.cemconres.2017.08.008>.
- Curosu, I., Muja, E., Ismailov, M., Ahmed, A.H., Liebscher, M., Mechtcherine, V., 2022. An experimental-analytical scale-linking study on the crack-bridging mechanisms in different types of SHCC in dependence on fiber orientation. *Cem. Concr. Res.* 152, 106650. <http://dx.doi.org/10.1016/j.cemconres.2021.106650>.
- Damineli, B.L., Kemeid, F.M., Aguiar, P.S., John, V.M., 2010. Measuring the eco-efficiency of cement use. *Cem. Concr. Compos.* 32 (8), 555–562. <http://dx.doi.org/10.1016/j.cemconcomp.2010.07.009>.
- de Paula Salgado, I., Conrad, F., Signorini, C., Günther, E., Ihlenfeldt, S., Mechtcherine, V., 2025a. Integrating life cycle assessment (LCA) and machine learning for sustainable designs: a case study on protective layers made of mineral-bonded fiber-reinforced composites. *Int. J. Life Cycle Assess.* 1–20. <http://dx.doi.org/10.1007/s11367-025-02454-7>.
- de Paula Salgado, I., Günther, E., Mechtcherine, V., 2025b. Integrated sustainability and resilience assessments of concrete infrastructures subjected to hazards: A systematic literature review. *Sustain. Resilient Infrastruct.* <http://dx.doi.org/10.1080/23789689.2025.2471119>.
- EuroFibers, 2012. Dyneema® fact sheets. URL <https://issuu.com/eurofibers/docs/name8f0d44>. (Accessed February 2026).
- Finnveden, G., Eldh, P., Johansson, J., 2006. Weighting in LCA based on ecotaxes-development of a mid-point method and experiences from case studies. *Int. J. Life Cycle Assess.* 11, 81–88. <http://dx.doi.org/10.1065/lca2006.04.015>.
- Gettu, R., Patel, A., Rathi, V., Prakasan, S., Basavaraj, A., Palaniappan, S., Maity, S., 2019. Influence of supplementary cementitious materials on the sustainability parameters of cements and concretes in the Indian context. *Mater. Struct.* 52, 1–11. <http://dx.doi.org/10.1617/s11527-019-1321-5>.
- Guinée, J., 2001. Handbook on life cycle assessment — operational guide to the ISO standards. *Int. J. Life Cycle Assess.* 6 (5), 255. <http://dx.doi.org/10.1007/bf02978784>.
- Habert, G., Denarié, E., Šajna, A., Rossi, P., 2013. Lowering the global warming impact of bridge rehabilitations by using ultra high performance fibre reinforced concretes. *Cem. Concr. Compos.* 38, 1–11. <http://dx.doi.org/10.1016/j.cemconcomp.2012.11.008>.
- Hajiesmaeili, A., Pittau, F., Denarié, E., Habert, G., 2019. Life cycle analysis of strengthening existing RC structures with R-PE-UHPFRC. *Sustainability* 11 (24), 6923. <http://dx.doi.org/10.3390/su11246923>.
- Van den Heede, P., Mignon, A., Habert, G., De Belie, N., 2018. Cradle-to-gate life cycle assessment of self-healing engineered cementitious composite with in-house developed (semi-) synthetic superabsorbent polymers. *Cem. Concr. Compos.* 94, 166–180. <http://dx.doi.org/10.1016/j.cemconcomp.2018.08.017>.
- Huang, X., Huang, Z., Zhou, Y., Hu, R., Hu, B., 2025. Life cycle assessment and cost analysis of LC³ concrete considering sustainability and uncertainty. *J. Build. Eng.* 111960. <http://dx.doi.org/10.1016/j.jobte.2025.111960>.

- I.F.G. International Fibres Group, (n.d.) IFG – Polypropylene (PP) Fibres. Technical data sheet. Available at: <https://fibresgroup.com/products/pp/>, (Accessed September 2025).
- International Organization for Standardization, 2006a. ISO 14040. Environmental management - life cycle assessment - principles and framework. URL <https://www.iso.org/standard/38498.html>.
- International Organization for Standardization, 2006b. ISO 14044. Environmental management - life cycle assessment - requirements and guidelines. URL <https://www.iso.org/standard/38498.html>.
- International Organization for Standardization, 2019a. ISO 14007. Environmental management – Guidelines for determining environmental costs and benefits. Geneva, Switzerland.
- 2019b. ISO 14008. Monetary valuation of environmental impacts and related environmental aspects. International Organization for Standardization, Geneva, Switzerland.
- Jungclaus, M.A., Williams, S.L., Arehart, J.H., Srubar III, W.V., 2024. Whole-life carbon emissions of concrete mixtures considering maximum CO₂ sequestration via carbonation. *Resour. Conserv. Recycl.* 206, 107605. <http://dx.doi.org/10.1016/j.resconrec.2024.107605>.
- Kanagaraj, B., Anand, N., Alengaram, U.J., Raj, R.S., Karthick, S., 2024. Limestone calcined clay cement (LC³): A sustainable solution for mitigating environmental impact in the construction sector. *Resour. Conserv. Recycl. Adv.* 21, <http://dx.doi.org/10.1016/j.rcradv.2023.200197>.
- Keoleian, G.A., Kendall, A., Dettling, J.E., Smith, V.M., Chandler, R.F., Lepech, M.D., Li, V.C., 2005. Life cycle modeling of concrete bridge design: Comparison of engineered cementitious composite link slabs and conventional steel expansion joints. *J. Infrastruct. Syst.* 11 (1), 51–60. [http://dx.doi.org/10.1061/\(ASCE\)1076-0342\(2005\)11:1\(51\)](http://dx.doi.org/10.1061/(ASCE)1076-0342(2005)11:1(51)).
- Kumar, S., Rai, D.C., 2023. Development of engineered cementitious composite with moderate tensile properties using polyester fibers. *Constr. Build. Mater.* 404, 133158. <http://dx.doi.org/10.1016/j.conbuildmat.2023.133158>.
- Leon-Miquel, M., Silva-Retamal, J., Aparicio, D., Rangelov, M., Jin, Q., Paul, A., 2023. Novel application of Chilean natural pozzolan for sustainable strain-hardening cementitious composite. *Resour. Conserv. Recycl.* 197, 107098. <http://dx.doi.org/10.1016/j.resconrec.2023.107098>.
- Li, X., Lv, X., Zhou, X., Meng, W., Bao, Y., 2022. Upcycling of waste concrete in eco-friendly strain-hardening cementitious composites: Mixture design, structural performance, and life-cycle assessment. *J. Clean. Prod.* 330, 129911. <http://dx.doi.org/10.1016/j.jclepro.2021.129911>.
- Liao, Q., Yu, J.-T., Dong, F.-Y., Fediuk, R., Yu, K.-Q., 2024. Tension-shear characteristics, cost and environmental impact of polyethylene fiber reinforced engineered cementitious composites: the role of fiber content. *Constr. Build. Mater.* 428, 136312. <http://dx.doi.org/10.1016/j.conbuildmat.2024.136312>.
- Lin, X., Yu, J., Li, H., Lam, J.Y., Shih, K., Sham, I.M., Leung, C.K., 2018. Recycling polyethylene terephthalate wastes as short fibers in strain-hardening cementitious composites (SHCC). *J. Hazard. Mater.* 357, 40–52. <http://dx.doi.org/10.1016/j.jhazmat.2018.05.046>.
- Malacarne, C.S., da Silva, M.R.C., Danieli, S., Maciel, V.G., Kirchheim, A.P., 2021. Environmental and technical assessment to support sustainable strategies for limestone calcined clay cement production in Brazil. *Constr. Build. Mater.* 310, 125261. <http://dx.doi.org/10.1016/j.conbuildmat.2021.125261>.
- Matthey, A., Büniger, B., 2019. Methodenkonvention 3.0 zur Ermittlung von Umweltkosten: Kostensätze, Stand 02/2019. Technical Report, Umweltbundesamt, Dessau-Roßlau.
- Miller, S.A., Horvath, A., Monteiro, P.J.M., 2018. Impacts of booming concrete production on water resources worldwide. *Nat. Sustain.* 1 (1), <http://dx.doi.org/10.1038/s41893-017-0009-5>.
- Nikbin, I.M., Dezhampannah, S., Charkhtab, S., Mehdipour, S., Shahvareh, I., Ebrahimi, M., Pourmasir, A., Pourghorban, H., 2022. Life cycle assessment and mechanical properties of high strength steel fiber reinforced concrete containing waste PET bottle. *Constr. Build. Mater.* 337, 127553. <http://dx.doi.org/10.1016/j.conbuildmat.2022.127553>.
- Panesar, D.K., Seto, K.E., Churchill, C.J., 2017. Impact of the selection of functional unit on the life cycle assessment of green concrete. *Int. J. Life Cycle Assess.* 22 (12), <http://dx.doi.org/10.1007/s11367-017-1284-0>.
- Peng, J., Huang, L., Zhao, Y., Chen, P., Zeng, L., Zheng, W., 2013. Modeling of carbon dioxide measurement on cement plants. In: *Advanced Materials Research*. <http://dx.doi.org/10.4028/www.scientific.net/AMR.610-613.2120>.
- Pillai, R.G., et al., 2019. Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC³). *Cem. Concr. Res.* 118, <http://dx.doi.org/10.1016/j.cemconres.2018.11.019>.
- Pizzol, M., Weidema, B., Brandão, M., Osset, P., 2015. Monetary valuation in life cycle assessment: a review. *J. Clean. Prod.* 86, 170–179. <http://dx.doi.org/10.1016/j.jclepro.2014.08.007>.
- Rodrigues, A.L.M.V., Mendes, Á.Á.F., Gomes, V., Battagin, A.F., Saade, M.R.M., Da Silva, M.G., 2022. Environmental and mechanical evaluation of blended cements with high mineral admixture content. *Front. Mater.* 9, 880986. <http://dx.doi.org/10.3389/fmats.2022.880986>.
- Schneider-Marin, P., Lang, W., 2020. Environmental costs of buildings: monetary valuation of ecological indicators for the building industry. *Int. J. Life Cycle Assess.* 25, 1637–1659. <http://dx.doi.org/10.1007/s11367-020-01784-y>.
- Schultze, W., Trommer, R., 2012. The concept of environmental performance and its measurement in empirical studies. *J. Manag. Control.* 22 (4), 375–412. <http://dx.doi.org/10.1007/s00187-011-0146-3>.
- Scope, C., Vogel, M., Guenther, E., 2021. Greener, cheaper, or more sustainable: Reviewing sustainability assessments of maintenance strategies of concrete structures. *Sustain. Prod. Consum.* 26, 838–858. <http://dx.doi.org/10.1016/j.spc.2020.12.022>.
- Scrivener, K., Martirena, F., Bishnoi, S., Maity, S., 2018. Calcined clay limestone cements (LC³). *Cem. Concr. Res.* <http://dx.doi.org/10.1016/j.cemconres.2017.08.017>.
- Signorini, C., Bracklow, F., Hering, M., Butler, M., Leicht, L., Schubert, T., Beigh, M.A., Beckmann, B., Curbach, M., Mechtcherine, V., 2023. Ballistic limit and damage assessment of hybrid fibre-reinforced cementitious thin composite plates under impact loading. *J. Build. Eng.* 80, 108037. <http://dx.doi.org/10.1016/j.jobte.2023.108037>.
- Signorini, C., Nobili, A., 2022. Durability of fibre-reinforced cementitious composites (FRCC) including recycled synthetic fibres and rubber aggregates. *Appl. Eng. Sci.* 9, 100077. <http://dx.doi.org/10.1016/j.apples.2021.100077>.
- Signorini, C., Sola, A., Malchiodi, B., Nobili, A., 2022. Highly dissipative fiber-reinforced concrete for structural screeds. *J. Mater. Civ. Eng.* 34 (4), 04022022. [http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0004160](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0004160).
- United Nations Environment Programme (UNEP), 2019. Sand and Sustainability: Finding New Solutions for Environmental Governance of Global Sand Resources. Technical Report, GRID-Geneva, United Nations Environment Programme, Geneva, Switzerland.
- Vogtländer, J., 2016. A Practical Guide to LCA for Students, Designers and Business Managers: Cradle-to-Grave and Cradle-to-Cradle, Appendix IV Delft Academic Press, Delft.
- Wang, L., Rehman, N.U., Curosu, I., Zhu, Z., Beigh, M.A.B., Liebscher, M., Chen, L., Tsang, D.C., Hempel, S., Mechtcherine, V., 2021. On the use of limestone calcined clay cement (LC³) in high-strength strain-hardening cement-based composites (HS-SHCC). *Cem. Concr. Res.* 144, 106421.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part i): overview and methodology. *Int. J. Life Cycle Assess.* 21 (9), 1218–1230. <http://dx.doi.org/10.1007/s11367-016-1087-8>.
- Yun, Y.J., Jang, S.J., Yun, H.D., 2013. Damage tolerance of reinforced concrete (RC) beams with a layer of PE fiber reinforced strain-hardening cement composite (PE-SHCC). *Appl. Mech. Mater.* 372, 219–222. <http://dx.doi.org/10.4028/www.scientific.net/AMM.372.219>.
- Zhang, D., Yu, J., Wu, H., Jaworska, B., Ellis, B.R., Li, V.C., 2020. Discontinuous micro-fibers as intrinsic reinforcement for ductile engineered cementitious composites (ECC). *Compos. Part B: Eng.* 184, 107741. <http://dx.doi.org/10.1016/j.compositesb.2020.107741>.