



Life Cycle Assessment and Hotspot Analysis of Hybrid Basalt–Polypropylene Fibre-Reinforced Concrete for UTES Shaft Linings Considering Operational Energy Performance

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ABSTRACT:

Underground Thermal Energy Storage (UTES) systems rely on durable and thermally efficient shaft lining materials to ensure long-term operational performance and energy efficiency. This study presents a comparative Life Cycle Assessment (LCA) and hotspot analysis of three concrete scenarios developed for UTES shaft linings: a conventional mix, a hybrid basalt–polypropylene fibre-reinforced mix incorporating a polycarboxylate ether (PCE) admixture, and a nominal high-cement mix. The assessment was conducted using OpenLCA v2.4.1 with the Ecoinvent v3.9.1 database, following EN 15804:2019 + A2 and ISO 14044:2006 standards, and considering a cradle-to-operation system boundary (A1–A3 + B1).

The results indicate that raw material production (A1) is the dominant contributor to environmental impacts across all scenarios, primarily due to cement manufacturing, while the operational stage (B1), associated with electricity demand related to thermal behaviour, represents the second most significant contributor. Transportation (A2) and manufacturing (A3) stages showed comparatively minor impacts. The conventional mix exhibited the lowest overall environmental impacts, whereas the hybrid fibre-reinforced mix showed higher embodied impacts due to the environmental intensities of basalt and polypropylene fibres and chemical admixtures. The nominal mix recorded the highest global warming potential due to its higher cement content.

Despite its higher embodied impacts, the hybrid mix demonstrated superior thermo-mechanical and thermal performance, which may enhance long-term operational efficiency and durability of UTES shaft linings. The findings highlight a clear trade-off between embodied environmental impacts and in-service functional performance, emphasising the need for whole-life sustainability assessment in the design of advanced concrete materials for underground thermal energy storage applications.

Keywords: Life Cycle Assessment (LCA); Underground Thermal Energy Storage (UTES); Hybrid fibre-reinforced concrete; Thermal conductivity; Hotspot analysis; EN 15804.

1. Introduction

Underground Thermal Energy Storage (UTES) and Mine Thermal Energy Storage (MTES) systems are increasingly recognised as effective solutions for large-scale, low-carbon thermal energy storage in urban and post-industrial regions (Brown *et al.*, 2024).

These systems utilise underground shafts and cavities to store and recover heat seasonally, contributing to energy flexibility and decarbonisation of heating networks. The structural lining of these shafts is a critical component, as it must ensure long-term mechanical stability, hydraulic integrity, and reliable thermal performance under coupled thermo–hydro–mechanical loading conditions. Concrete is the most widely used material for shaft linings due to its high compressive strength, durability, and adaptability to underground construction (Barbhuiya and Das, 2023). However, conventional concrete mixtures may exhibit moderate thermal conductivity and limited resistance to cracking and permeability, which can influence the operational efficiency and service life of UTES systems. These limitations highlight the need for advanced concrete materials that deliver improved mechanical and thermal performance in aggressive underground environments.

Hybrid fibre-reinforced concrete incorporating basalt and polypropylene (PP) fibres has emerged as a promising solution for enhancing the performance of underground structural linings (Fiore *et al.*, 2016; Li *et al.*, 2024). Basalt fibres improve tensile strength and thermal stability, while polypropylene fibres enhance ductility and control microcrack

propagation. Together, these fibres can improve durability and resistance to thermo-mechanical stresses, which are critical for long-term operation of UTES shaft lining systems (Yu *et al.*, 2023). In addition, improved thermal conductivity may contribute to more efficient heat transfer and enhanced operational energy performance (Fleuchaus *et al.*, 2018).

Despite these functional advantages, the inclusion of fibres and chemical admixtures can increase the embodied environmental impacts associated with the production and processing of raw materials. Therefore, it is essential to evaluate the trade-off between higher embodied impacts and improved in-service performance when assessing the sustainability of advanced concrete mixtures for UTES applications. Life Cycle Assessment (LCA) provides a systematic framework for quantifying environmental impacts across different life cycle stages and identifying dominant processes and environmental hotspots (Hoxha *et al.*, 2020).

Previous LCA studies of concrete materials have predominantly focused on embodied impacts during production, particularly in Modules A1–A3. However, for UTES shaft linings, the operational phase (Module B1) is also significant, as thermal behaviour influences operational electricity demand associated with heat transfer through the lining. The integration of experimentally informed thermal performance considerations into LCA modelling remains limited in the literature, especially for hybrid fibre-reinforced

concrete designed for subsurface thermal energy storage systems.

This study therefore presents a comparative Life Cycle Assessment and hotspot analysis of three concrete

scenarios developed for UTES shaft linings: a conventional mix (1:2:4), a hybrid basalt–polypropylene fibre-reinforced mix incorporating a polycarboxylate ether (PCE) admixture, and a nominal high-cement mix (1:2:3). The assessment was conducted using OpenLCA v2.4.1 with the Ecoinvent v3.9.1 database, following EN 15804:2019 + A2 and ISO 14044:2006 standards, and applying the CML 2016 impact assessment method. The system boundary includes Modules A1–A3 (raw material supply, transport, and manufacturing) and Module B1 representing operational energy performance during the use phase.

The objective is to identify environmental hotspots across life-cycle stages and to evaluate the trade-off between higher embodied impacts and improved thermomechanical performance of hybrid fibre-reinforced concrete. The results provide insight into the relative sustainability of advanced concrete materials for UTES shaft lining applications and support informed material selection based on whole-life environmental and support informed material selection based on whole-life environmental performance considerations.

2. Materials and Methods

2.1 Concrete Scenarios

Three concrete scenarios were developed and evaluated in this study to represent potential shaft lining materials for Underground Thermal Energy Storage (UTES) applications. The first scenario corresponds to a conventional concrete mix (1:2:4) commonly used in structural applications and considered as the baseline

reference. The second scenario is a hybrid fibre-reinforced concrete incorporating basalt fibres and polypropylene (PP) fibres, along with a polycarboxylate ether (PCE) superplasticiser, designed to enhance mechanical strength,

crack resistance, and thermal performance. The third scenario is a nominal mix with a higher cement content (1:2:3), representing a more binder-intensive formulation typically associated with higher strength but increased environmental impacts.

The hybrid fibre-reinforced mix was specifically designed to improve the durability and thermo-mechanical performance of shaft linings under cyclic thermal loading and aggressive underground conditions. Basalt fibres contribute to improved tensile strength and thermal stability, while polypropylene fibres enhance ductility and control microcrack propagation. These combined effects are expected to influence both the structural integrity and thermal behaviour of the lining material during long-term operation.

2.2 Life Cycle Assessment Framework:

The Life Cycle Assessment (LCA) was performed in accordance with ISO 14044:2006 and EN 15804:2019+A2. The modelling was carried out using OpenLCA v2.4.1 software with background data sourced from the Ecoinvent v3.9.1 database. The CML 2016 impact assessment method was employed to quantify environmental impacts across multiple midpoint categories.

The functional unit was defined as 1 m³ of concrete used as shaft lining material for UTES systems. This functional unit enables a consistent comparison between the three concrete scenarios in terms of both embodied and operational environmental performance.

2.3 System Boundary and Assumptions

The system boundary adopted in this study covers Modules A1–A3 and Module B1, in line with the EN 15804 modular framework. Modules A1–A3 include raw material extraction and processing, material transport to the manufacturing site, and concrete production. Module B1 represents the use phase, specifically accounting for operational heat loss

associated with the shaft lining's thermal performance.

Typical UK transport distances were assumed in the modelling, including road freight for raw materials such as aggregates and cement. Heavy-duty Euro 6 lorries were

considered for material transportation to ensure alignment with representative European transport datasets available in Ecoinvent. All calculations were performed per functional unit within OpenLCA, and the results were generated in both absolute values and relative percentages to identify dominant processes and environmental hotspots.

2.4 Integration of Thermal Performance into B1 Module

To better represent the operational performance of UTES shaft linings, the thermal behaviour of the investigated concrete mixes was explicitly considered in the LCA modelling. The hybrid fibre-reinforced concrete exhibited higher thermal conductivity than the conventional mix, which can affect the magnitude of heat loss during system operation.

In this study, the operational module (B1) was conceptualised to reflect the effect of thermal conductivity on heat transfer through the shaft lining. Higher thermal conductivity is associated with more efficient heat transfer and reduced thermal gradients (Barbhuiya and Das, 2023, Mankel, Caggiano and Koenders, 2019), which may improve thermal regulation and potentially reduce operational energy losses in UTES systems. By incorporating the thermal performance of the concrete mixes into the B1 stage, the assessment provides a more realistic representation of long-term environmental performance.

2.5 Impact Assessment and Hotspot Analysis

The environmental impacts were calculated for each life cycle stage and impact category using the CML 2016 method. The results were analysed to identify the dominant contributors to overall impacts, including key materials (e.g., cement, aggregates, fibres) and life-cycle stages (A1–A3 versus B1). Hotspot analysis was

conducted by comparing the relative contribution of each stage and process to the total environmental burden for each concrete scenario.

This approach enables the evaluation of trade-offs

between higher embodied impacts associated with advanced materials and the potential operational benefits arising from improved mechanical, durability, and thermal performance of hybrid fibre-reinforced concrete in UTES shaft lining applications.

3. Results and Discussion

3.1 Stage-wise Environmental Impact Analysis

The stage-wise analysis of life-cycle impacts revealed that the raw-material production stage (A1) is the dominant contributor to the overall environmental burden across all concrete scenarios. This stage accounts for approximately 65–75% of total impacts across key categories, including climate change, acidification, and eutrophication, primarily due to cement manufacturing and raw material processing (Flower and Sanjayan, 2007). The high contribution of A1 confirms the well-established environmental intensity of cement production and its central role in embodied emissions of concrete systems (Hoxha *et al.*, 2020).

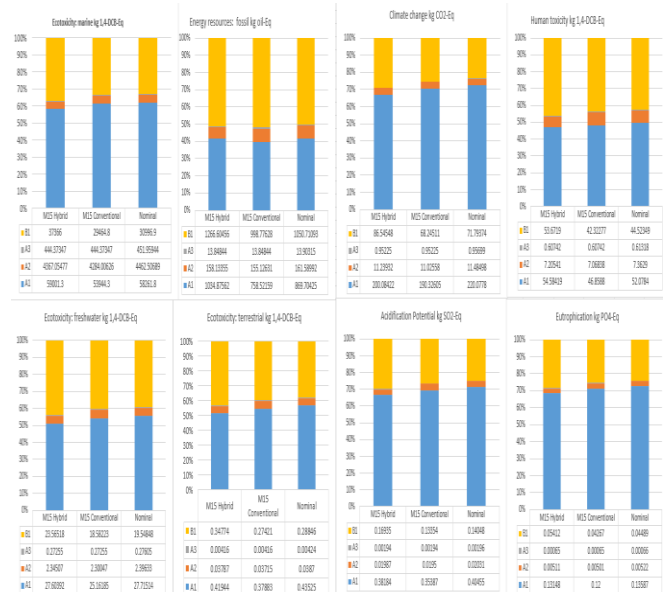


Figure 1: Stage-wise contribution of life cycle modules (A1–A3 and B1) to total environmental impacts of the investigated concrete scenario

The operational stage (B1), representing electricity demand associated with heat transfer through the shaft lining during UTES operation, was identified as the second-most-

significant contributor. Depending on the impact category, B1 accounted for approximately 24–44% of total impacts and was the dominant stage for fossil energy resource depletion. This highlights the importance of considering operational energy performance when evaluating materials for underground thermal energy storage applications.

In contrast, the transportation stage (A2) contributed relatively little, typically 3%-8%, reflecting the assumed UK transport distances for aggregates and cement. The manufacturing stage (A3) exhibited the lowest impacts (approximately 0.3–0.7%), as it mainly involves electricity and water consumption during batching and mixing operations. These findings confirm that environmental mitigation strategies should primarily focus on material production (A1) and operational energy performance (B1), as these stages account for the majority of life-cycle impacts.

3.2 Comparison of Environmental Impacts among Concrete Scenarios

The aggregated life cycle impact results demonstrate clear differences among the three investigated concrete scenarios: conventional, hybrid fibre-reinforced, and nominal high-cement mixes. Overall, the conventional mix exhibited the lowest environmental impacts across most categories, while the hybrid mix showed the highest impacts, except for global warming potential (GWP), where the nominal mix slightly exceeded the hybrid formulation.

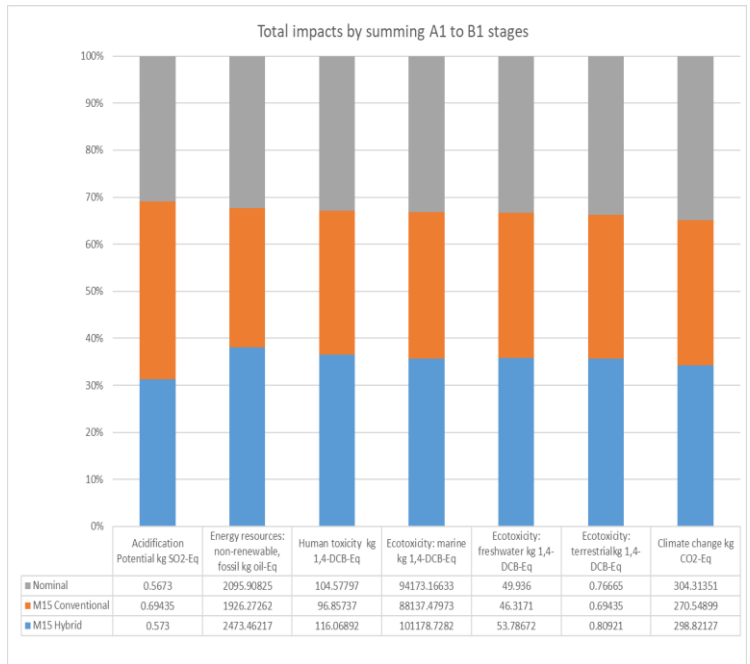


Figure 2: Aggregated environmental impact comparison of conventional, hybrid, and nominal concrete mixes across selected impact categories.

The higher impacts associated with the hybrid mix can be attributed to the additional embodied energy and environmental intensity of basalt fibres, polypropylene fibres, and the PCE admixture. Although these components constitute a relatively small fraction of the total mass, their production processes are energy-intensive, thereby increasing fossil energy demand and ecotoxicity-related impacts. Consequently, the hybrid mix recorded the highest values in categories such as abiotic depletion of fossil resources, acidification, eutrophication, and marine ecotoxicity.

The nominal mix, characterised by a higher cement content, exhibited the highest GWP values, confirming the dominant influence of cement production on climate change impacts.

Conversely, the conventional mix, with moderate cement content and no fibre additives, consistently demonstrated the lowest environmental impacts, making it the most environmentally favourable option when considering only the A1–A3 and B1 stages.

These results highlight a clear trade-off: while advanced hybrid fibre-reinforced concrete enhances functional performance, it also increases embodied environmental impacts compared with conventional concrete mixtures.

Table 1: Life Cycle Impact Assessment (LCIA) results for the three concrete scenarios (A1–A3 + B1) per functional unit (1 m³ of concrete).

Impact Category	Unit	Conventional (A)	Hybrid (B)	Nominal ©
GWP ₁₀₀ Global Warming Potential	kg CO ₂ -eq	270.59	298.82	304.31
ADP (Fossil Fuels)	MJ	1,955.5	2,043.1	2,018.7
ODP (Ozone Depletion Potential)	kg CFC-11-eq	1.81E-05	1.91E-05	1.88E-05
AP (Acidification Potential)	kg SO ₂ -eq	0.471	0.512	0.505
EP (Eutrophication Potential)	kg PO ₄ ³⁻ -eq	0.187	0.203	0.195
MAETP (Marine Aquatic Eco-toxicity Potential)	kg 1,4-DCB-eq	6.41E ⁴	7.25E ⁴	6.94E ⁴

3.3 Relative Contribution of Life Cycle Stages

The normalised stage comparison further illustrates the dominance of the A1 stage across most impact categories in all concrete scenarios. In the hybrid mix, A1 contributed the most to marine and human ecotoxicity, while B1 contributed the most to fossil energy resource depletion. For the nominal mix, A1 dominated categories such as climate change, freshwater ecotoxicity, terrestrial ecotoxicity, and acidification potential.

These trends confirm that raw material production, particularly cement manufacturing, is the primary driver of environmental impacts, whereas operational electricity demand significantly influences energy-related categories. The relative analysis also indicates that the hybrid mix tends to exhibit higher stage-wise

contributions in both A1 and B1 due to the combined effects of fibre production and thermal-performance-related operational energy considerations.

3.4 Hotspot Analysis

Hotspot analysis was conducted to identify the key processes and material inputs responsible for the observed environmental burdens. The results clearly demonstrate that cement production is the principal hotspot within the A1 stage, accounting for approximately 60–90% of impacts across several categories, particularly global warming potential and acidification (Flower and Sanjayan, 2007, Scrivener *et al.*, 2018). This finding aligns with the established literature, which indicates that cement manufacture accounts for the majority of concrete systems' embodied emissions.

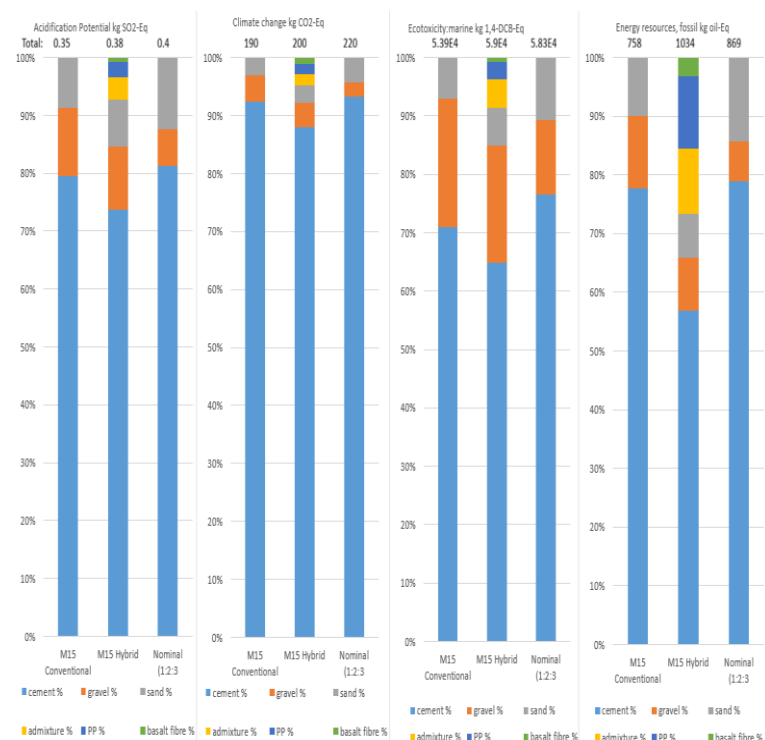


Figure 3: Hotspot analysis showing material-level contribution to environmental impacts, highlighting the dominance of cement production and the influence of fibre and admixture inputs.

Aggregates (sand and gravel) were identified as secondary contributors, with their relative importance

varying depending on mix proportions. In mixes with higher gravel content, gravel exhibited a larger share of impacts compared with sand, whereas in the nominal mix with altered proportions, sand contribution increased relative to gravel.

Despite their small mass fractions, basalt fibres, polypropylene fibres, and the PCE admixture exhibited

disproportionately high environmental intensities, particularly in the fossil energy depletion and ecotoxicity categories. This explains the elevated impacts observed for the hybrid mix, confirming that minor high-impact materials can significantly influence overall life cycle results.

For the operational stage (B1), electricity consumption emerged as the dominant hotspot, accounting for the majority of impacts within the use phase. This finding emphasises that decarbonising the electricity supply and optimising thermal performance are critical strategies for reducing the long-term environmental impacts of UTES shaft lining materials.

3.5 Trade-off between Embodied Impacts and In-Service Performance

The results reveal a clear trade-off between embodied environmental impacts and functional performance of the investigated concrete mixes. Although the hybrid basalt–polypropylene fibre-reinforced concrete exhibited higher impacts during production stages (A1–A3), it offers enhanced mechanical strength, improved crack resistance, and superior thermal conductivity compared with conventional concrete.

These improved thermo-mechanical properties are

particularly relevant for UTES shaft linings, where long-term durability and efficient thermal behaviour are essential for reliable system operation. Higher thermal conductivity can enhance heat-transfer efficiency within the lining, potentially improving operational energy performance and reducing electricity demand associated with heat losses over the service life.

Therefore, while the conventional mix demonstrates the lowest immediate environmental impacts, the hybrid mix may provide long-term sustainability benefits when whole-life performance, durability, and operational efficiency are considered (Pomponi and Moncaster, 2016). This highlights the importance of evaluating advanced construction materials beyond cradle-to-gate emissions and incorporating performance-related considerations into sustainability assessments.

3.6 Interpretation of Overall Environmental Performance

From a cradle-to-operation perspective (A1–A3 + B1), the conventional mix represents the most environmentally favourable option due to its lower embodied impacts and absence of energy-intensive fibre additives. The nominal mix, with a higher cement content, had the greatest global warming impacts, reaffirming the critical influence of cement dosage on climate change emissions.

The hybrid mix, although associated with moderately higher embodied impacts, demonstrated a balanced sustainability profile when functional performance is considered. Its enhanced mechanical properties suggest longer service life and reduced maintenance requirements, while its improved thermal conductivity may contribute to better operational energy behaviour in UTES systems. Consequently, the hybrid mix can be

viewed as a performance-oriented sustainable alternative, particularly in applications where durability and thermal efficiency are critical design criteria.

Overall, the results confirm that cement production and operational electricity demand are the two primary environmental hotspots driving the life cycle impacts of UTES shaft lining concrete. Effective mitigation strategies should therefore focus on reducing cement-related emissions through material optimisation and improving operational energy performance through enhanced thermal design and low-carbon electricity supply.

Conclusion

This study presented a comparative Life Cycle Assessment (LCA) and hotspot analysis of three concrete scenarios developed for Underground Thermal Energy Storage (UTES) shaft linings: a conventional mix, a hybrid basalt–polypropylene fibre-reinforced mix with PCE admixture, and a nominal high-cement mix. The assessment was conducted using OpenLCA with the Ecoinvent database, following EN 15804 and ISO 14044 frameworks, and considering a cradle-to-operation system boundary (A1–A3 + B1).

The results demonstrated that the raw material production stage (A1) is the dominant contributor to environmental impacts, primarily due to cement

manufacturing, which accounted for the majority of global warming and acidification burdens. The operational stage (B1), associated with electricity demand linked to thermal behaviour of the shaft lining, was identified as the second most influential stage, particularly for fossil energy resource depletion. In contrast, transportation (A2) and manufacturing (A3) stages contributed relatively minor impacts.

Among the investigated mixes, the conventional concrete exhibited the lowest overall environmental impacts across most categories, whereas the hybrid fibre-reinforced concrete showed higher embodied impacts due to the inclusion of basalt fibres, polypropylene fibres, and chemical admixtures. The nominal mix, characterised by a higher cement content, had the highest global warming potential, confirming the strong influence of cement dosage on climate-related emissions.

Despite its higher embodied impacts, the hybrid mix demonstrated superior thermo-mechanical performance, including enhanced strength, durability, and thermal conductivity. These properties are particularly advantageous for UTES shaft linings, where long-term structural integrity and efficient thermal behaviour are essential. Consequently, the hybrid concrete offers potential operational and durability-related benefits that may compensate for its higher production impacts when evaluated from a whole-life performance perspective.

Overall, the study highlights the importance of considering both embodied emissions and in-service functional performance in the sustainable design of UTES shaft lining materials. Future optimisation should focus on reducing cement-related emissions by using

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supplementary cementitious materials and on improving operational energy performance through enhanced thermal design and low-carbon electricity supply.

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