

# Climate Change Impact of Innovative Structural Aluminium Reinforced Concrete, a Case Study in Norway

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**Abstract.** The most common structural material used in the construction sector is steel-reinforced concrete. However, concrete cracking and reinforcement corrosion demand constant monitoring as well as timely and costly maintenance activities. Furthermore, concrete has substantial environmental impacts, being responsible for about 7% of total CO<sub>2</sub> emissions worldwide. Innovative materials in construction engineering have been studied with the goal of improving the sector's environmental performance, mostly by reducing cement content in concrete. In this context, assessing the environmental profile of such innovations is essential to avoid shifting environmental burdens elsewhere. This study evaluates the climate change impact of a novel reinforced concrete that incorporates calcined blue clay as a supplementary cementitious material and Aluminium (Al) as reinforcement. Using a cradle-to-gate Life Cycle Assessment (LCA), the climate change impact of this innovative material is compared with that of conventional steel-reinforced concrete. The result show that the climate change impact of the innovative concrete is 46% less than that of the incumbent solution. Acknowledging the early development stage of the new concrete and the limitation regarding data robustness, this work contributes to the problem-solution space and provides direction to further explore possibilities for fully unlocking the new material's potential, so it can outperform the incumbent one in terms of greenhouse gas emissions in the future.

## Introduction

Concrete is one of the most widely used materials in the construction sector. However, it has substantial environmental impacts, mainly due to its cement content. Cement production alone is responsible for around 7% of global CO<sub>2</sub> emissions [1]. Demand for cement continues to grow: its production has increased by a factor of 34 over the last six decades, while the world population has grown by only a factor of 3 [2]. In the context of today's sustainability goals, innovation in concrete is therefore essential.

Innovation in concrete technology includes the development of new mix designs, materials, and application techniques, driven by environmental regulations, rising performance requirements, and resource scarcity. Many recent studies focus on cement/clinker substitution using supplementary cementitious materials (SCMs), aiming to improve both environmental and mechanical performance [3]. However, Pushkar and Verbitsky (2016) [4] highlight that higher levels of clinker substitution do not necessarily lead to lower environmental impacts. Consequently, other research has turned to optimized mix designs that reduce cement content through the incorporation of recycled materials and industrial by-products [3].

The environmental burdens of the construction sector are closely linked to its intensive consumption of natural resources and energy, high waste generation, and significant greenhouse gas emissions. To address these challenges, the sector is pursuing strategies such as improving process energy efficiency, reducing waste and emissions, and optimizing designs through material and mass

reduction [5,6]. Focusing on concrete, in building structures, it is often used in combination with steel reinforcement [7]. Steel reinforcement requires relatively thick concrete cover layers to protect the steel from early corrosion and structural deterioration. This requirement increases material consumption and associated impacts. As a result, there is an urgent need for alternatives to conventional steel-reinforced concrete that can support a more climate-friendly construction sector. One such innovation is Aluminium reinforced concrete, which combines corrosion-resistant Aluminium with a specially designed, low-pH concrete mix. This novel concrete system is the focus of the present study.

Achieving low greenhouse gas emissions in construction demands the redesign of both materials and processes. Comparing the climate change impact of such innovations is crucial to ensure that the burden is mitigated rather than shifted elsewhere in the life cycle. Life Cycle Assessment (LCA), as defined in the ISO 14000 series, provides a framework to identify environmental hotspots across a product's life cycle [8].

The objective of this study is to compare the climate change impacts of traditional steel reinforced concrete with those of innovative Aluminium reinforced concrete using LCA. The results will help identify climate change hotspots and support the adaptation and further development of a novel, climate friendly construction material, with the aim of offering a solution that addresses both current needs and future challenges.

### State-of-the-Art in Concrete Innovation

Concrete has been used for long in the construction industry due to its versatility, strength, durability, and affordability [5]. However, cement content in concrete is of environmental concern due to the energy-intensive processes associated with its production [5]. Alternative to traditional concrete, therefore, has been sought with potential to diminish these impacts. Furthermore, alternative production processes and supportive policies are imperative to assure emission reductions in the sector [5].

Literature has explored means to make concrete more sustainable, methods ranged from developing alternative binders, incorporating waste or by-products as concrete mix ingredients, improving material performance and durability, and reducing impact from production and application processes [9]. In this section, the state-of-the-art literature about concrete innovations and environmental performance will be reported.

Kouvara et al. (2023) [10] evaluated a polymer concrete incorporating recycled PET. Although resin production caused high impacts per kilogram, the material became environmentally advantageous at the component level (building) due to its low density and high strength, enabling up to 80% material savings.

Several low-energy and high-performance reinforced concrete were analyzed in Zingg et al. (2016) [11]. Hybrid wood–concrete slabs can reduce energy use by 50% and emissions by 70%. High performance concrete prestressed with carbon fibre reinforced polymer achieved ~60% energy and 70% emission savings per meter of beam compared to conventional reinforced concrete, while ultra-high performance fibre reinforced concrete with reduced clinker and synthetic fibres achieved over 50% savings per cubic meter.

Bio-inspired designs have also emerged. Horn et al. (2018) [6] demonstrated that a graded concrete optimized for bending loads could reduce climate impacts by 7–19%. Furthermore, biological approaches, such as self-healing bacterial concrete [5], promise up to 60% emission reductions by lowering maintenance needs and using bacteria grown on organic waste, though evidence remains largely qualitative. Bio-based materials like hemp concrete [12] show reduced life-cycle impacts due to improved building energy performance and CO<sub>2</sub> sequestration, despite burdens from lime binders in the composition of the hemp concrete.

The results of the research on recycled aggregates and supplementary cementitious materials of Daci and E. Mester-szab (2024) [9] indicates that system boundaries significantly influence LCA outcomes and that optimizing both binder and aggregate use is essential to avoid burden shifting. The

service life and engineering context of the innovative concrete also plays a role in the LCA results, as explored in the work of Jiang et al. (2025) [13] with high-performance glass pervious concrete. Other studies explored carbon-reducing mixes, including net-zero designs using carbonated recycled aggregates [14], mine tailings as sand replacements achieving modest 3% footprint reductions [15]. Finally, Kamath et al. (2025) [16] showed that carbonated cementitious materials initially have higher impacts at laboratory scale but may outperform conventional concrete when produced industrially under optimized energy and material conditions.

Alternative binders such as shea nutshell ash [17] can improve climate performance at  $\geq 15\%$  replacement rates. Waste-plastic concretes [18] showed that binder-based plastic mixes outperform plastic-filler mixes, with renewable energy offering up to 83% further emission reduction.

In construction technologies, 3D-printed concrete provides similar manufacturing impacts to traditional construction but reduces on-site emissions, lowering total carbon footprints [14].

Finally, Alfocea-Roig et al. (2024) [19] compare non-structural precast magnesium phosphate cement (MPC) made with magnesium from primary production and from steelmaking waste against ordinary Portland cement. MPC based on steelmaking residues shows markedly lower climate impacts (up to  $-42\%$  vs. Portland cement and  $-56\%$  vs. primary-magnesium MPC), while primary-magnesium MPC performs worse than Portland cement. Here lies the importance of carrying LCA, innovative clinker substitutes may not always yield environmental savings.

### Aluminium Reinforced Concrete

Literature agrees that the use of blended cement can reduce the impact of climate change per kg of cement by 42% between 2020 and 2025 [20]. The binder used in the concrete mix developed for this work is a blended cement with reduced clinker content. Besides cement, the concrete mix has seven other components, including supplementary cementitious materials, in proportions designed to hold Aluminium reinforcement, which cannot be disclosed here due to confidentiality aspects. However, characteristics and properties of the innovative concrete will be discussed shortly in this section.

The primary innovation of this concrete mix concerns its pH. Conventional concrete is highly alkaline, which leads to hydrogen evolution and degradation of Aluminium reinforcement. In contrast, the new mix is formulated with an acidic pH that prevents these reactions and preserves Aluminium integrity. This is achieved by replacing 55% of the cement with calcined blue clay, combined with a water–cement ratio of approximately 0.43. The Aluminium reinforcement itself consists of about 92% Aluminium scrap.

The innovative concrete offers several potential benefits: reduced concrete cover requirements for the reinforcement, no maintenance associated with carbonation- or chloride-induced corrosion, a higher water-to-binder ratio enabling easier casting and lower plasticizer demand, and accelerated carbonation, which enhances CO<sub>2</sub> uptake and thus reduces the overall carbon footprint.

The new Aluminium-reinforced concrete can be engineered to meet specific strength requirements and is primarily intended for structural road applications. However, ongoing development work is still determining which structural types and use cases are most suitable for this innovation.

### Life Cycle Assessment

Life Cycle Assessment (LCA) is a systematic and holistic approach to analyze a product or service's environmental effects, also enabling pinpointing environmental hotspots. Through it, LCA supports well-informed ecological decisions. The LCA methodology application is guided by the International Organization for Standardization (ISO) norms 14040 and 14044 [8], followed in this study, comprising four phases: goal and scope definition; life cycle inventory; life cycle impact assessment; interpretation.

The main goal of this study's LCA is to compare the climate change impact of two different reinforced concrete materials for structural applications with similar workability (water/ cement ratio) and mechanical properties. Consequently, the study aims to assess and compare the climate change

impact of steel-reinforced concrete and Aluminium-reinforced concrete, identifying environmental hotspots.

The functional unit of this assessment is 1 slab of reinforced concrete with a nominal axle load of 3.3 ton intended for structural applications in road infrastructure. The innovative Aluminium-reinforced concrete slab was engineered to satisfy the same load-bearing and stiffness requirements as the steel-reinforced slab. Because steel relies on standard rebar while Aluminium uses an optimized hollow extruded profile, the two slabs differ in geometry.

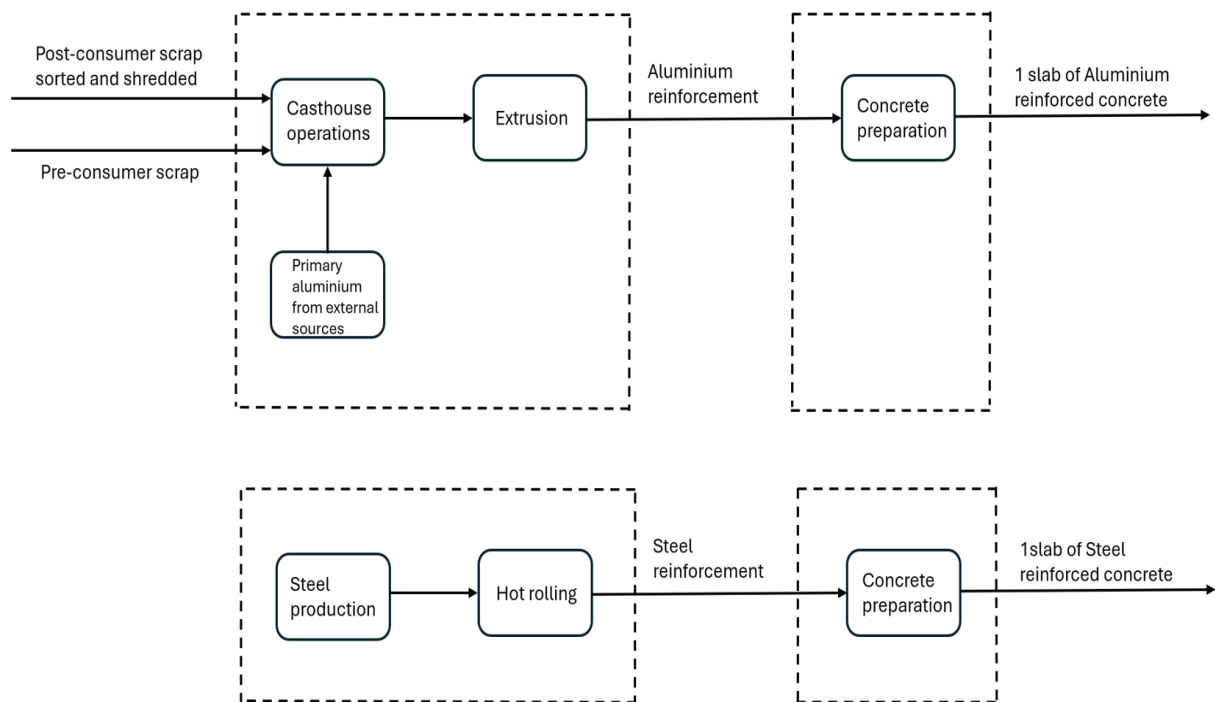
Structural equivalence between the two solutions was verified using mechanical performance data provided by Alugreen project partners. The Aluminium-reinforced slab requires a smaller concrete volume (2.16 m<sup>3</sup> compared with 6 m<sup>3</sup> for the steel-reinforced version), due to both the material characteristics (a low-pH concrete mix that improves stress distribution) and the reduced concrete cover made possible by Aluminium's corrosion resistance. The slab volumes were defined to ensure equal structural capacity (ultimate bending moment), identical serviceability performance (deflection), and consistency with reinforcement-to-concrete interaction behavior observed in laboratory tests.

The geographical context of the study is Norway. This attributional LCA study uses the database Ecoinvent v. 3.11 cut-off prioritizing process on the geographical order Norway>Europe>Global.

The boundary of the studied system is from cradle to gate, and it considers all flows of materials, energy, and emissions from raw materials extraction until manufacturing. The use and end-of-life phases are excluded from the scope. Furthermore, in this study, transport is not considered because all materials are deemed to be manufactured in the same location.

The system boundary is reported in the flowchart of Fig. 1. Foreground processes are represented; background processes are not depicted to avoid cluttering of the illustration. Multifunctionality is addressed by cut-off, remarks go to the post and pre-consumer scrap flows (recycled Aluminum): for the first, burdens are accounted upstream the studied system, meaning that it enters the studied system burden free; for the latter, it is modeled as closed-loop recycling, meaning that it contains the embodied impacts of the initial material. The latter modeling concretizes using a co-product allocation approach. This conservative approach is adopted and recommended by the Aluminum producer partner involved in the case study because pre-consumer scrap is also sourced in the market. Current, the market for pre-consumer scrap is competitive, with prices as high as primary Aluminium's price. In addition, the fact that 40% of Aluminium's worldwide production ends up as pre-consumer scrap, strengthens the adoption of the co-product allocation approach, assuring that burdens are really accounted, avoiding greenwashing.

The inventory data used in this study originates majorly from a Norwegian Aluminium producer and a Norwegian research institution involved in developing the innovative concrete under the Alugreen project, a major Norwegian research and innovation initiative focused on circular Aluminium solutions. Due to a confidentiality agreement, the full inventory data cannot be publicly disclosed, but it can be highlighted that 92% of the reinforcement alloy consists of Aluminium scrap and the rest 8% of primary Aluminium, which is added in the alloy mix due to mechanical property requirements. An exception is the data source for the inventory of the extrusion process, which is adapted from the report of European Aluminium (2025) [21].



**Fig. 1.** System boundaries and foreground processes for Aluminium and steel reinforced concrete (functional unit: 1 slab of Aluminium-reinforced concrete with a nominal axle load of 3.3 ton intended for structural applications in road infrastructure and 1 slab of steel-reinforced concrete with a nominal axle load of 3.3 ton intended for structural applications in road infrastructure). Source: author's own.

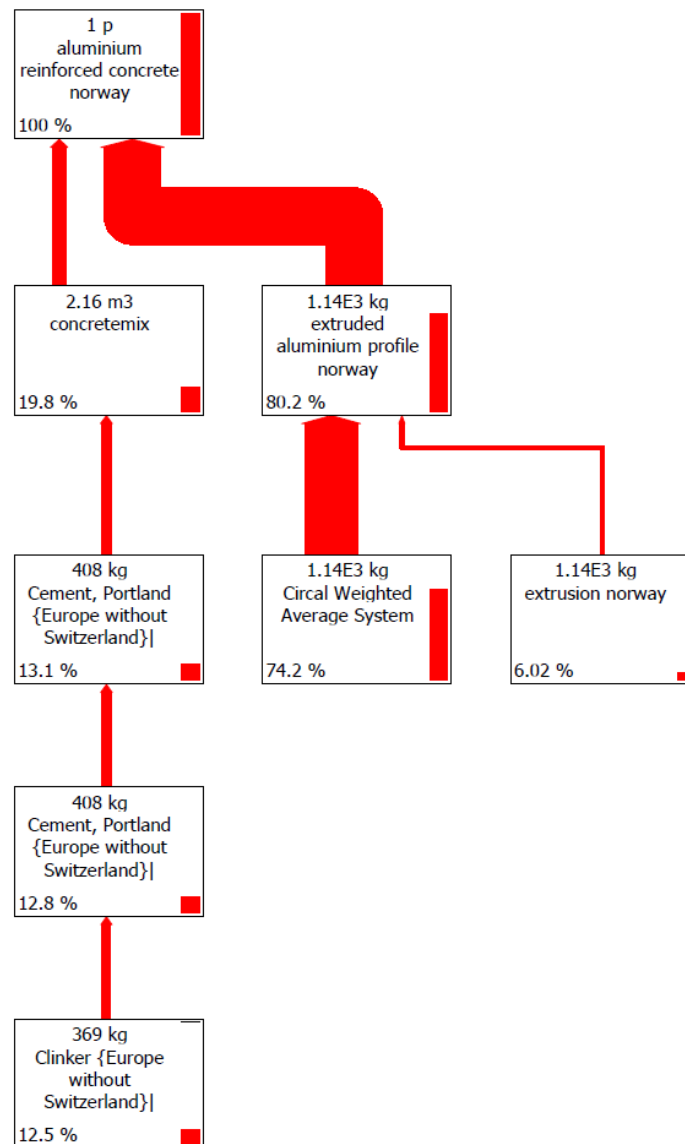
The impact category chosen in the impact assessment phase is climate change, with the indicator global warming potential GWP 100a, which quantifies the global warming potential over a timeframe of 100 years in terms of kg of CO<sub>2</sub>eq. The GWP 100a method is part of the Environmental Footprint method family, which is a recommended impact assessment method by the European Union [22]. The single focus on the climate change impact category is justified by assuming that if the new reinforced concrete does not have favorable characteristics in terms of greenhouse gas emissions, its future market viability is compromised due to the low emission direction envisaged in the construction sector. Therefore, the climate change impact category can be seen as a feasibility starting point for materials innovations in the construction industry [19].

The quantitative interpretation phase of the LCA will follow in the Results and Discussion sections.

## Results

### Aluminium reinforced concrete

Fig. 2 shows the climate change impact network for the innovative Aluminium reinforced concrete. The contribution of unit processes towards the total impact of the studied functional unit is indicated by the width of the connecting arrows. On the flow chart, "1p" corresponds to 1 slab. The node cut-off is set to 5%.

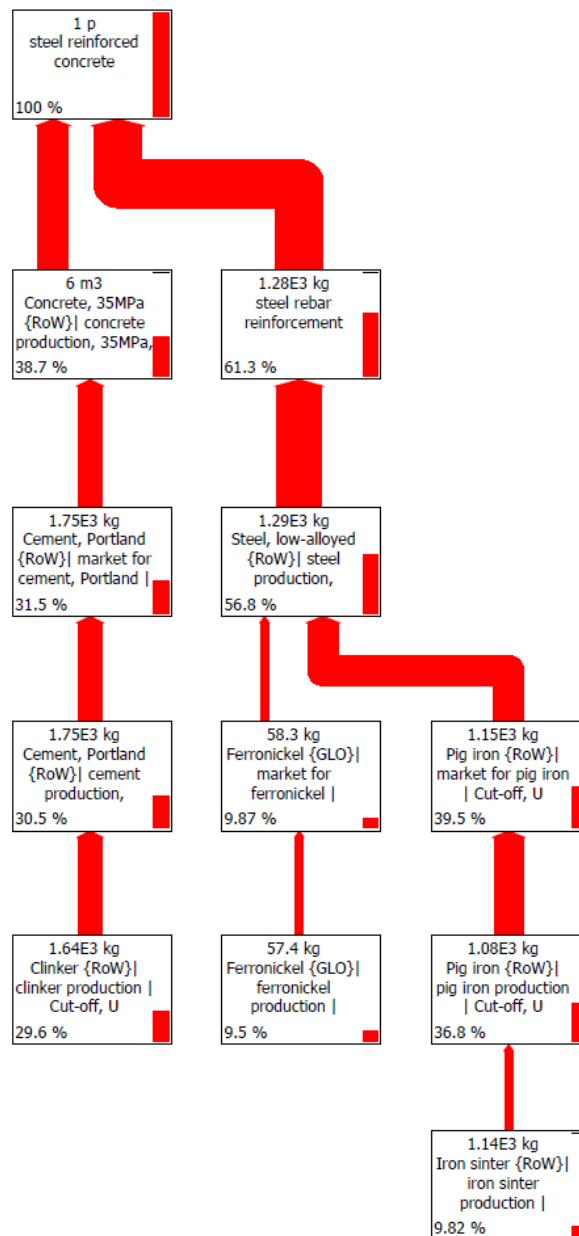


**Fig. 2.** Climate change contribution analysis for 1 slab of Aluminium-reinforced concrete with a nominal axle load of 3.3 ton intended for structural applications in road infrastructure. Source: Simapro network.

The contribution analysis of the innovative reinforced concrete highlights a successful effort in reducing the influence of cement on the impact of a construction material. However, the Aluminium reinforcement becomes the largest contributor, accounting for 80.2%. The innovative concrete, besides not being the highest impact contributor towards the innovative reinforced concrete, still reveals the role of clinker as a major influencer in climate change, accounting for 12.5% out of the 13.1% of Portland cement's contribution.

### Steel reinforced concrete

Fig. 3 shows the climate change impact network for the incumbent steel reinforced concrete. The contribution of unit processes towards the total impact of the studied functional unit is indicated by the width of the connecting arrows. On the flow chart, "1p" corresponds to 1 slab. The node cut-off is set to 9.5%.



**Fig. 3.** Climate change contribution analysis for 1 slab of steel-reinforced concrete with a nominal axle load of 3.3 ton intended for structural applications in road infrastructure. Source: Simapro network

The contribution analysis of the traditional steel reinforced concrete reveals that the steel reinforcement contributes the most, with 61.3%, followed by the concrete, which has clinker accounting for about 80% of its contribution. In steel production, pig iron production has a considerable contribution, mainly with iron sinter production, which accounts for about 25% of pig iron's contribution, indicating high emissions during ore preparation.

Table 1 compares the climate change indicator results between the functional units of the two reinforced concrete:

**Table 1.** Climate change profile of the compared alternatives. FU: 1 slab of Aluminium-reinforced concrete with a nominal axle load of 3.3 ton intended for structural applications in road infrastructure and 1 slab of steel-reinforced concrete with a nominal axle load of 3.3 ton intended for structural applications in road infrastructure. Source: author's own.

	Climate change impact [kg CO <sub>2</sub> eq]
Aluminium reinforced concrete	2740
Steel reinforced concrete	5060

The innovative concrete is about 46% less emissive than the incumbent alternative for the same functional unit. It is important to note here that the dimensional volume of 1 slab of Aluminium reinforced concrete is 2.16 m<sup>3</sup>, and that of 1 slab of steel reinforced concrete with the same structural properties is 6 m<sup>3</sup>.

## Discussion

The LCA methodology is mainly used for the environmental assessment of innovative construction materials, as it allows identification of environmental bottlenecks and suggestions for potential improvements.

The climate change impact of two structural construction materials is compared in this work, being one of the materials an innovation in the field without approved applications, as it is found for the incumbent material. The results show that a focus on the reduction of cement's greenhouse gas emissions can increase the emissions contribution of the reinforcement by 33%, shifting environmental concerns from concrete to the reinforcement. Furthermore, the results underscore the importance of evaluating recycled materials' environmental performance: recycled Aluminium does not have less climate change impact than primary steel in the analyzed context, leading to higher overall impact from the reinforcement. The use of heating in Aluminium's extrusion is also highlighted, suggesting a sensitivity analysis on the combustion material for heating to further enhance the climate change performance of the innovative reinforced concrete.

One must be attentive that the mass of concrete and reinforcement in the two analyzed reinforced concretes is not the same. The common structural properties and safety in the new material are achieved with a decrease of 64% in concrete mass and of 11% in reinforcement mass due to the material properties provided by the innovative concrete mix and Aluminium. On this account, considering the application of the innovative concrete in an infrastructure leads to design innovation that can yield significant material reduction in construction, and so greenhouse gas emissions reduction. Zingg et al. (2016) [11] support the latter, affirming that looking at structural levels containing the innovative material, and the whole life cycle of the structure, can access potential environmental savings. This is of relevance for Aluminium, because it is a naturally corrosion free material, which can save maintenance related emissions in infrastructure.

## Conclusion and Suggestion for Future Work

The achievement of CO<sub>2</sub> emission reduction in the construction sector can only progress further with the implementation of innovative technologies and materials together with different policy frameworks and regulations [22, 23]. This work evaluated the climate change impact of an innovative construction material, Aluminium reinforced concrete, through a LCA. The LCA results show a favorable result for the innovative material when compared to the incumbent solution, steel reinforced concrete. A reduction of 46% in greenhouse gas emissions is achieved by comparing the production of 1 slab of each material.

This study's climate change impact results motivate to broaden the scope of the LCA to include the utilization of the innovative concrete in a practical application, in a cradle-to-grave approach. Literature suggests that looking into structural levels containing the innovative concrete can reveal deeper potential environmental savings. This is particularly relevant for Aluminium due to its corrosion resistance and almost infinite recycling properties. Furthermore, acknowledging that the

innovation is at an early development stage, another suggestion is to integrate future socio-economic scenarios, based on projections from Integrated Assessment Models (IAMs), modifying background process inventories and projecting them into the future when industrial scale is reached [24, 25, 26]. This prospective LCA can enhance the robustness of the analysis by identifying improvements needed on background supply chains that can make the innovative concrete outperform the incumbent one [28].

In addition, conducting a supplementary analysis that includes recycled steel within the scope can provide valuable insights by enabling an early comparison of climate-change performance, should recycled steel become the incumbent solution. Furthermore, including recycled steel in the analysis enhances the completeness for the assessment of the innovative solution.

### Limitations and Contributions of the Work

This study is empirical and relies on data from both laboratory and industrial scale processes to assess the climate change impact of an innovative reinforced concrete slab through an LCA. While part of the life cycle inventory benefits from having real industrial production data from one of the project partners, the other part of the inventory relies on less robust data from laboratory experiments, since the innovation is not fully mature yet, thus, not representing optimized industrial conditions. The laboratory-scale data were scaled up to the best of the authors' knowledge to enable a comprehensive comparison and full-scale environmental assessment. Therefore, assumptions have been made regarding its viability as a commercial product and the energy requirements during its manufacturing, so one should acknowledge the existence of uncertainties in the results.

Besides the data limitation, the LCA of this work contributes to the problem-solution space, suggesting anticipated meaning without waiting for all the information to be available, thus providing strategic questions, engagement, and direction to forward-looking research activities, including the improvement of the innovative concrete design to understand the implications of different choices on the climate change impact performance of the material.

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### References

- [1] Y. Dong, "Performance assessment and design of ultra-high performance concrete (UHPC) structures incorporating life-cycle cost and environmental impacts," vol. 167, pp. 414–425, 2018, doi: 10.1016/j.conbuildmat.2018.02.037.
- [2] U. N. Environment, K. L. Scrivener, V. M. John, E. M. Gartner, É. Polytechnique, and F. De Lausanne, "Cement and Concrete Research Eco-efficient cements: Potential economically viable solutions for a low-CO<sub>2</sub> cement-based materials industry ☆," *Cem. Concr. Res.*, vol. 114, no. June, pp. 2–26, 2018, doi: 10.1016/j.cemconres.2018.03.015.
- [3] A. Balasaheb, "ADVANCED CONCRETE TECHNOLOGIES FOR SUSTAINABLE INFRASTRUCTURE DEVELOPMENT: A STATE-OF-THE-ART," vol. 4, no. 2, pp. 319–325, 2022.
- [4] S. Pushkar, O. Verbitsky, and S. Á. R. Á. Anova, "Effects of different allocation approaches for modeling mineral additives in blended cements on environmental damage from five concrete mixtures in Israel," *Mater. Struct.*, vol. 49, no. 10, pp. 4401–4415, 2016, doi: 10.1617/s11527-016-0796-6.
- [5] B. Bewket and M. Walied, "Bio-based bacterial concrete: a sustainable alternative in construction," pp. 1–13, 2025.

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- [6] R. Horn *et al.*, “Bio-inspiration as a Concept for Sustainable Constructions Illustrated on Graded Concrete,” vol. 16, pp. 742–753, 2019.
- [7] A. Martínez-rocamora and M. Marrero, “LCA databases focused on construction materials : A review,” vol. 58, pp. 565–573, 2016, doi: 10.1016/j.rser.2015.12.243.
- [8] T. Iso and I. Standards, “Environmental management The ISO 14000 family of International Standards ISO in brief ISO and the environment.”
- [9] A. Daci and E. Mester-szab, “Case Studies in Construction Materials Life cycle assessment of concrete incorporating all concrete recycling products,” vol. 21, no. June, 2024.
- [10] A. Kouvara, C. Priavolou, D. Ott, P. Scherer, and V. H. Van Zyl-bulitta, “Construction,” pp. 1–20, 2023.
- [11] D. E. T. H. Zürich, “Expanding Boundaries : Systems Thinking for the Built Environment,” no. August, 2016, doi: 10.3218/3774-6.
- [12] S. Pretot, F. Collet, and C. Garnier, “Life cycle assessment of a hemp concrete wall : Impact of thickness and coating,” *Build. Environ.*, vol. 72, pp. 223–231, 2014, doi: 10.1016/j.buildenv.2013.11.010.
- [13] X. Jiang, J. Lu, X. Zhao, W. Tian, T. Liu, and Z. Leng, “Material design and structural optimization of sustainable high-performance pervious concrete for engineering application,” *Constr. Build. Mater.*, vol. 495, no. August, p. 143591, 2025, doi: 10.1016/j.conbuildmat.2025.143591.
- [14] J. A. O. Barros, *4th fib International Conference on Concrete Sustainability*, vol. 2. .
- [15] N. Garcia-troncoso, H. Baykara, M. H. Cornejo, A. Riofrio, M. Tinoco-hidalgo, and J. Flores-rada, “Case Studies in Construction Materials Comparative mechanical properties of conventional concrete mixture and concrete incorporating mining tailings sands,” vol. 16, no. January, pp. 1–12, 2022, doi: 10.1016/j.cscm.2022.e01031.
- [16] D. Kamath *et al.*, “Science of the Total Environment Towards low-carbon low-energy concrete alternatives : Life cycle assessment of carbonated cementitious material-based precast panels ☆,” *Sci. Total Environ.*, vol. 976, no. March, p. 179279, 2025, doi: 10.1016/j.scitotenv.2025.179279.
- [17] S. Oyebisi and T. Alomayri, “Cement-based concrete modified with *Vitellaria Paradoxa* ash : A lifecycle assessment,” *Constr. Build. Mater.*, vol. 342, no. May, p. 127906, 2022, doi: 10.1016/j.conbuildmat.2022.127906.
- [18] H. Goyal, R. Kumar, and P. Mondal, “Life cycle analysis of paver block production using waste plastics : Comparative assessment with concrete paver blocks,” *J. Clean. Prod.*, vol. 402, no. March, p. 136857, 2023, doi: 10.1016/j.jclepro.2023.136857.
- [19] A. Alfocea-roig, A. Müller, B. Steubing, J. Giro-paloma, J. Formosa, and S. Huete-hern, “Life cycle assessment of the climate change impact of magnesium phosphate cements formulated with tundish descaling waste compared to conventional cement,” vol. 42, no. July, pp. 1–15, 2024.
- [20] M. Georgiades, I. Hussain, B. Steubing, C. Cheeseman, and J. Myers, “Resources , Conservation & Recycling Prospective life cycle assessment of European cement production,” *Resour. Conserv. Recycl.*, vol. 194, no. April, p. 106998, 2023, doi: 10.1016/j.resconrec.2023.106998.
- [21] European Aluminium, “Life Cycle Inventory (LCI) data for aluminium production and transformation processes in Europe ENVIRONMENTAL PROFILE REPORT FOR,” no. May, 2025.

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- [22] S. Biganzioli, F. De Laurentiis, and S. Diaconu, *Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods*. 2018.
- [23] K. Kermeli *et al.*, “The scope for better industry representation in long-term energy models : Modeling the cement industry,” *Appl. Energy*, vol. 240, no. January, pp. 964–985, 2019, doi: 10.1016/j.apenergy.2019.01.252.
- [24] A. Font, L. Soriano, S. Maria, D. M. Pinheiro, and M. M. Tashima, “Design and properties of 100 % waste-based ternary alkali-activated mortars : Blast furnace slag , olive-stone biomass ash and rice husk ash Monz o,” vol. 243, 2020, doi: 10.1016/j.jclepro.2019.118568.
- [25] A. M. Beltran, B. Cox, C. Mutel, and D. P. Van Vuuren, “When the Background Matters Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment,” vol. 24, no. 1, 2018, doi: 10.1111/jiec.12825.
- [26] R. Sacchi *et al.*, “PRospective EnvironMental Impact asSEment ( premise ): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models IMAGE,” *Renew. Sustain. Energy Rev.*, vol. 160, no. April 2021, p. 112311, 2022, doi: 10.1016/j.rser.2022.112311.
- [27] P.J. Joyce and A. Björklund, “Methods, Tools, Data, and Soft Ware Futura assessment,” pp. 134-144, 2022, doi: 10.1111/jiec.13115.
- [28] D. De Souza, L. Matt, R. Sedrik, L. Vares, and F. Cherubini, “Integrating ex-ante and prospective life-cycle assessment for advancing the environmental impact analysis of emerging bio-based technologies,” vol. 43, no. November, pp. 319–332, 2023, doi: 10.1016/j.spc.2023.11.002.