Evaluating the Environmental Impact of Alkali-Activated Concrete: A Life Cycle Assessment of Blast Furnace and Ladle Slag Binders

Tariq G. Ahmed*, Sina R. Gomari, Kamal E. Gomari, and David Hughes

School of Computing, Engineering and Digital Technology, Teesside University, Middlesbrough, United Kingdom
Email: t.ahmed@tees.ac.uk (T.G.A.); s.rezaei-gomari@tees.ac.uk (S.R.G.); kamal.elyasi91@gmail.com (K.E.G.); d.j.hughes@tees.ac.uk (D.H.)
*Corresponding author

Manuscript received March 5, 2025; accepted April 27, 2025; published June 13, 2025

***Abstract*—The production of Ordinary Portland Cement (OPC) significantly contributes to global CO_2 emissions. This study investigates substituting OPC with Blast-furnace Slag (BFS) and Ladle Slag (LS) in concrete through a comprehensive Life Cycle Analysis (LCA). Among five mixes tested, a LS blend achieved a 98% reduction in Global Warming Potential (from 431.6 to 8.2 kg CO_2 eq per m³) and showed notable carbon sequestration (81.4 kg CO_2 eq). However, the results also highlight that high alkali activator content can exacerbate other impacts, such as Terrestrial Ecotoxicity and Fine Particulate Matter Formation. These findings emphasize the need for balanced concrete formulations that minimize carbon emissions without compromising other environmental performance metrics.**

***Keywords*—alkali-activated materials, Blast-Furnace Slag (BFS), environmental impact assessment, Ladle slag (LS), Life Cycle Analysis (LCA), ordinary portland cement, sustainable concrete**

I. Introduction

Concrete remains indispensable in modern construction but carries substantial environmental burdens due to Ordinary Portland Cement (OPC) production, which accounts for roughly 8% of global CO_2 emissions [1]. Rising global urbanization further compounds ecological concerns, including overexploitation of raw materials like sand and significant carbon outputs [2]. Consequently, there is growing interest in alternative materials such as Blast-furnace Slag (BFS), Ladle Slag (LS), fly ash, and silica fume to reduce concrete's carbon footprint [3, 4]. BFS, formed via quenching molten slag from high-temperature iron production, has been found to enhance concrete durability and strength [5]. LS, a by-product of secondary steel refining, contains high calcium content and can accelerate concrete hardening [6].

Recent research has examined various Supplementary Cementitious Materials (SCMs) in geopolymer concretes. Studies show that substituting OPC with SCMs can halve the environmental impact of concrete without sacrificing performance [7]. Additionally, certain by-products like biochar and filter cake can sequester CO_2 and potentially achieve carbon-negative outcomes under specific conditions [8]. Building on these insights, our prior work demonstrated that LS exhibits superior CO_2 sequestration compared to BFS, especially when temperature and reaction duration are optimized [9].

Against this backdrop, the present study conducts a comprehensive Life Cycle Analysis (LCA) to evaluate the environmental impacts of concrete produced from OPC, BFS, and LS, extending beyond previous LCAs to include carbonation potential [10]. Our findings aim to guide sustainable construction practices by assessing whether these alternative binders can move concrete from a significant CO_2 source to a viable carbon sink, ultimately supporting broader strategies for climate-change mitigation and eco-friendly infrastructure development.

II. Material Selection and Methods

A. Cementitious Materials

The two cementitious materials selected for this study, in addition to ordinary Portland cement, are Blast-Furnace Slag (BFS) and Ladle Slag (LS). Both were sourced from Port Talbot and ground to a particle size of 63 µm (see Fig. 1). Singh *et al.* [7] provided the percentage chemical composition of OPC, similarly, the percentage compositions of BFS and LS are shown in Fig. 2. The surface morphology of both uncarbonated and carbonated BFS and LS, as examined using Scanning Electron Microscopy (SEM), is presented in Fig. 3.

Fig. 1. Ground materials: BFS (left) and LS (right).

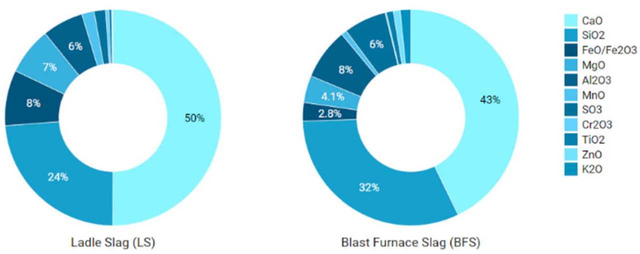

Fig. 2. Chemical compositions of BFS (left) and LS (right).

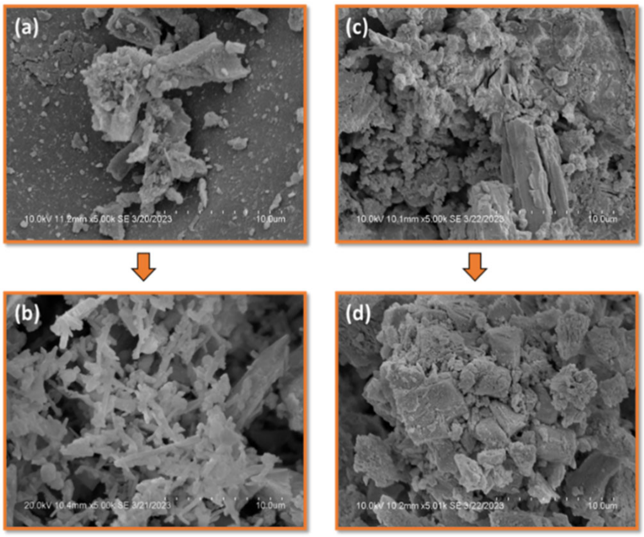

Fig. 3. SEM images of uncarbonated (a and c) and carbonated (b and d) BFS.

Alkali activators are necessary for geopolymer cement for several reasons. They trigger the polymerisation process by dissolving silicon and aluminium atoms, thereby producing a solution that reorganises into a gel, which then hardens to form geopolymer concrete [7]. Furthermore, they improve the reactivity of the waste-derived cementitious materials and enhance the mechanical performance of the geopolymer cement [11]. Sodium silicate and sodium hydroxide solutions were selected as alkaline activators.

B. *Concrete Mixes and Preparation*

Five concrete mixes (Table 1) were formulated: Mix 1 is a standard OPC blend, while Mixes 2–5 introduce varying BFS, LS, and alkali activator proportions. In laboratory-scale tests, materials were mixed for 60 seconds using tap water, with specimens cast in plastic molds. For industrial-scale considerations, power consumption was estimated using commercially available mixers and vibrating block-making machines.

Table 1. Concrete mixes used for LCA

Material (kg)	Mix_1	Mix_2	Mix_3	Mix_4	Mix_5
Coarse aggregate	1398.19	1398.19	1398.19	1398.19	1398.19
Fine aggregate	339.98	339.98	339.98	339.98	339.98
Water	200	200	200	200	200
OPC	490	245	200	0	0
BFS	0	245	0	543	0
LS	0	0	290	0	543
Sodium silicate	0	142.86	142.86	21.4	21.4
Sodium hydroxide	0	19.88	19.88	21.4	21.4
Total	2428.17	2590.91	2590.91	2523.97	2523.97

C. *CO_2 Sequestration Analysis*

BFS and LS powders were combined with water in controlled ratios and exposed to CO_2 in a pressure vessel (20–90 ± 2 °C for 1–4 days). Reaction by-products were then filtered, and dissolved carbonates measured to quantify mineral carbonation. Additional characterization techniques FT-IR, SEM, XRD, TGA, and the Scheibler method provided insights into the mineralogical and chemical changes of the slag samples.

D. *Curing Conditions*

Geopolymer specimens were steam-cured at 60 °C in a thermally insulated chamber. The total heat requirement was calculated (Eq. (1)–(4)) based on mass, specific heat capacity, and temperature gradient, accounting for both the initial heating and heat losses through the chamber's walls.

$$Q_{curing} = Q_{heating} + Q_{maintaining\ temp} \tag{1}$$

$$Q_{curing} = m_{gp} \times C_{p,gp} \times \Delta T \tag{2}$$

$$Q_{maintaining\ temp} = U_o \times A_s \times \Delta T \tag{3}$$

$$U_o = \left[\frac{1}{h_i} + \sum \frac{x_w}{k_w} + \frac{1}{h_o}\right]^{-1} \tag{4}$$

III. LCA Methodology

Life Cycle Assessment (LCA) is an ISO-defined methodology for quantifying the environmental impacts of a product or process across its entire lifespan, from raw material extraction through to end-of-life disposal (ISO 14,040 and 14,044). In this study, an attributional LCA approach was employed to evaluate how integrating steel slag additives Blast-Furnace Slag (BFS) and Ladle Slag (LS) in Geopolymer Concrete (GPC) could reduce carbon emissions. The carbon capture potential of BFS and LS, previously studied by Gomari *et al.* [9], served as a key input to the LCA.

The functional unit was set at the production of one cubic metre of concrete, measured in kg CO_2-equivalent emissions (kg CO_2-e/kg). Five mixes were assessed: an Ordinary Portland Cement (OPC) reference mix, plus four variations incorporating BFS and LS in different proportions. The cradle-to-gate system boundary shown in Fig. 4 covered raw material extraction, transportation, processing, and production. Emissions from energy consumption, chemical reactions, and transport were included, whereas infrastructure, equipment manufacture, and human resource factors fell outside the scope. BFS and LS were considered waste materials, and thus only their downstream processing and transport emissions were included. Potential material losses during aggregate and SCM production were assumed negligible; in cases with limited data, secondary information from literature was adopted.

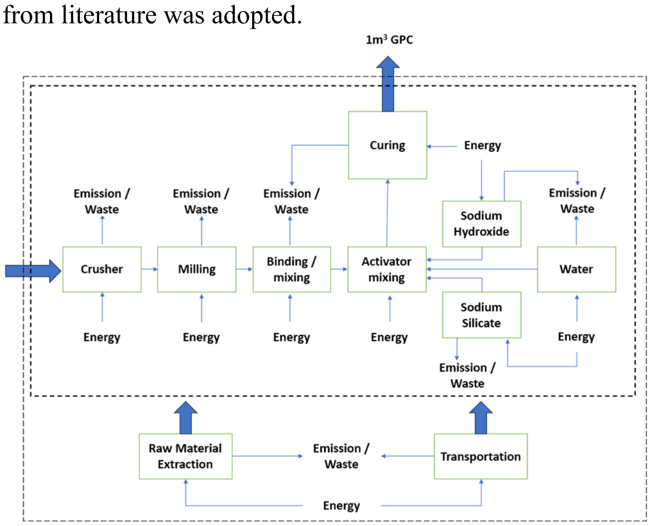

Fig. 4. System boundary for GPC.

The inventory phase integrated experimental carbon-sequestration findings with the theoretical capacity of BFS and LS to bind CO_2 using Eq. (5). This potential offset was incorporated into the total CO_2 footprint of each mix. All material and energy flows were compiled in Simapro 9.4.0.3, which drew on public datasets, industrial sources, and scientific publications. The impact assessment employed the ReCiPe 2016 Midpoint H and Endpoint H methods to capture a broad spectrum of environmental burdens. Midpoint indicators included Global Warming Potential (GWP), Stratospheric Ozone Depletion (SOD), Fine Particulate Matter Formation (FPMF), Terrestrial Acidification (TA), Terrestrial Eutrophication (TE), Marine Eutrophication (ME), Marine Ecotoxicity (MET), Human Carcinogenic Toxicity (HCT), and Human Non-Carcinogenic Toxicity (HNCT). These midpoint categories provided granular insights into how specific emissions influence distinct environmental processes, such as acidification, eutrophication, or toxicity.

$$R_{CO2} = \frac{M_{CO2}}{100}\left(\frac{\%CaO}{M_{CaO}} + \frac{\%MgO}{M_{MgO}}\right) \times \omega \qquad (5)$$

where RCO_2 is the sequestration potential in tonnes of CO_2 eq per tonne of mineral; MMgO, MCaO, and MCO_2 are the molecular masses of MgO, CaO and CO_2; %CaO and %MgO are the percentages in weight of CaO and MgO in the rock; and ω is a factor that accounts for the additional sequestration that occurs when cations are transported to the ocean and remain dissolved.

Meanwhile, the Endpoint H method consolidated these impacts under broader classifications affecting human health, ecosystem diversity, and resource availability, offering a more strategic perspective on the overall sustainability of each mix. For emerging technologies like geopolymer concretes, complete LCAs can be challenging due to limited data; however, targeted scope boundaries and conservative assumptions can still generate meaningful results. By evaluating both midpoint and endpoint categories, the study balances detailed impact analysis (useful for material selection and process optimization) with an overarching view of sustainability goals.

IV. Results and Discussion

A. Mid-Point Impact

Table 2 presents the midpoint environmental impact assessment of the five concrete mixes, highlighting variations across different impact categories. Mix 1, which relies on conventional OPC, exhibits the highest Global Warming Potential (GWP) at 431 kg CO_2 eq., whereas Mix 5 shows a significant reduction to 8.2 kg CO_2 eq., indicating a much lower environmental impact. Stratospheric Ozone Depletion (SOD) values are negligible across all mixes, while the incorporation of alternative materials in Mixes 4 and 5 reduces Fine Particulate Matter Formation (FPMF), Ozone Formation in Terrestrial Ecosystems (OFTE), and Terrestrial Acidification (TA).

Table 2. Results of midpoint impact assessment

Impact Category	Mix_1	Mix_2	Mix_3	Mix_4	Mix_5
GWP (kg CO2 eq)	431.6272	368.8945	290.5767	62.5168	8.2168
SOD (kg CFC11 eq)	0.0000	0.0002	0.0002	0.0001	0.0001
FPMF (kg PM2.5 eq)	0.2401	0.4165	0.3913	0.1332	0.1332
OFTE (kg NOx eq)	0.7190	0.7582	0.6844	0.2175	0.2175
TA (kg SO2 eq)	0.6591	0.9286	0.8583	0.2863	0.2863
ME (kg N eq)	0.0033	0.0082	0.0079	0.0030	0.0030
TET (kg 1,4-DCB)	310.6724	1358.7799	1282.8937	886.3036	886.3036
MET (kg 1,4-DCB)	5.0099	17.8234	17.3010	5.6629	5.6629
HCT (kg 1,4-DCB)	6.9156	15.9756	15.3605	6.0331	6.0331
HNCT (kg 1,4-DCB)	93.8504	277.1557	267.2893	93.0791	93.0791

However, Mixes 2 and 3 show substantially higher values in toxicity categories, including Terrestrial Ecotoxicity (TET), Marine Ecotoxicity (MET), Human Carcinogenic Toxicity (HCT), and Human Non-Carcinogenic Toxicity (HNCT). This increase is primarily due to the high quantities of alkali activators, particularly sodium silicate, indicating a trade-off when substituting OPC with certain waste materials. While Mixes 2 and 3 reduce GWP compared to Mix 1 (213 kg CO_2 eq. and 170 kg CO_2 eq., respectively), their environmental benefits are offset by increased toxicity impacts. In contrast, mix 5 demonstrates the lowest GWP and further benefits from CO_2 capture of 81.4 kg CO_2 eq. due to ladle slag incorporation. These results highlight the need for a balanced approach when selecting alternative concrete materials, considering both carbon reduction and broader environmental impacts.

B. End Point Impact

The environmental impact assessment of five different concrete mixes was conducted, focusing on three key categories: human health, ecosystems, and resources as shown in Fig. 5. Among the Mixes, Mix 2 exhibited the highest negative impact across all three categories, primarily due to its high sodium silicate and Ordinary Portland Cement (OPC) content. The human health impact was significant for both Mix 2 and Mix 3, as sodium silicate contributes to health risks through pollutant emissions and increased water alkalinity, while OPC is associated with respiratory issues and carbon-intensive production processes. In contrast, Mixes 4 and 5 demonstrated the lowest human health impact due to their minimal alkali activator content and the absence of OPC, making them the least harmful options in this category.

The ecosystem impact assessment revealed similar trends, with Mix 2 having the highest negative effect, followed closely by Mix 1. This was largely attributed to sodium silicate and OPC, which disrupt aquatic ecosystems, contribute to acid rain, and accelerate land degradation and biodiversity loss. Mix 3 exhibited slightly lower, yet still notable, ecological impacts. In comparison, Mixes 4 and 5 had the least detrimental effect on ecosystems due to their reduced reliance on these materials, resulting in less disruption to aquatic and terrestrial habitats.

For resource consumption, Mix 2 demonstrated the highest impact due to the energy-intensive production of sodium silicate and OPC. Mix 3 and Mix 1 had significant resource demands, reflecting their material composition. Mixes 4 and 5 required fewer natural resources and less energy for production, making them more sustainable alternatives.

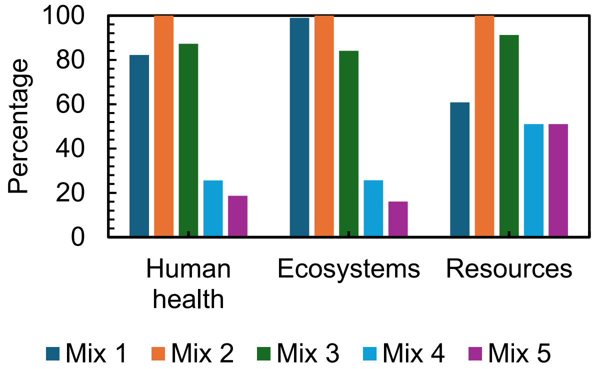

Fig. 5. Endpoint environmental impact assessment.

The ecosystem impact assessment revealed similar trends, with Mix 2 having the highest negative effect, followed closely by Mix 1. This was largely attributed to sodium silicate and OPC, which disrupt aquatic ecosystems, contribute to acid rain, and accelerate land degradation and biodiversity loss. Mix 3 exhibited slightly lower, yet still notable, ecological impacts. In comparison, Mixes 4 and 5 had the least detrimental effect on ecosystems due to their reduced reliance on these materials, resulting in less disruption to aquatic and terrestrial habitats.

In terms of resource consumption, Mix 2 again demonstrated the highest impact due to the energy-intensive production of sodium silicate and OPC. Mix 3 and Mix 1 also had significant resource demands, reflecting their material composition. Conversely, Mixes 4 and 5 required fewer natural resources and less energy for production, making them more sustainable alternatives.

V. Conclusion

This life cycle analysis highlights the environmental trade-offs associated with different concrete mixes, emphasizing the importance of a holistic approach in material selection. The study confirms the significant atmospheric impact of Ordinary Portland Cement (OPC), as seen in Mix 1, which recorded a high Global Warming Potential (GWP) of 431 kg CO_2 eq. In contrast, Mix 5, incorporating Ladle Slag (LS), achieved a remarkable 98% reduction, lowering its GWP to just 8.2 kg CO_2 eq. This demonstrates the potential of alternative materials to mitigate climate change impacts effectively.

However, while reducing OPC usage generally decreases the carbon footprint, the study identifies a key concern: replacing OPC with materials requiring high levels of alkali activators, such as sodium silicate and sodium hydroxide, can lead to adverse environmental consequences. Mixes 2 and 3, despite having a lower GWP than OPC-based concrete, showed significantly higher impacts in other categories, particularly Terrestrial Ecotoxicity (TET), due to the high quantities of alkali activators contributing to toxicity and ecosystem degradation.

The findings underscore the need for a balanced assessment of concrete mix components, considering not only carbon reduction but also broader environmental and health impacts. While materials such as Blast Furnace Slag (BFS) and LS offer promising sustainability benefits, their overall environmental trade-offs must be carefully evaluated. This study advocates for a nuanced approach to sustainable construction, ensuring that strategies to mitigate climate change do not inadvertently exacerbate other environmental challenges.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

T. G. Ahmed: Conceptualization, Data curation, Formal analysis, Methodology, Writing, reviewing, and editing. S. R. Gomari: Conceptualization, Formal analysis, Methodology, Resources, Supervision, Validation, Writing—review & editing. K. E. Gomari: Validation, Writing, reviewing and editing. D. Hughes: Resources, Supervision, Validation, Writing—review & editing; all authors had approved the final version.

Funding

This work was supported by the Mevocrete project (Project code:10030207) through UK Research and Innovation (UKRI), which was a collaboration with nine other industrial partners. We thank to Material Evolution for providing the samples that were used in this study.

Acknowledgment

The authors thank the skilled and helpful technician team in the Engineering department at Teesside University for their outstanding support.

References

[1] R. M. Andrew, "Global CO_2 emissions from cement production, 1928–2018," *Copernicus GmbH,* Nov. 2019. doi: 10.5194/essd-11-1675-2019

[2] G. Schiller and J. Roscher, "Impact of urbanization on construction material consumption: A global analysis," *J. Ind. Ecol.*, 2023.

[3] A. Kumar Parashar, P. Sharma, and N. Sharma, "A study of GGBS based cement concrete with the inclusion of waste foundry sand on mechanical properties," *Mater Today Proc*, vol. 62, pp. 4134–4139, 2022. doi: https://doi.org/10.1016/j.matpr.2022.04.663

[4] O. Najm, H. El-Hassan, and A. El-Dieb, "Ladle slag characteristics and use in mortar and concrete: A comprehensive review," *Elsevier Ltd.*, Mar. 2021. doi: 10.1016/j.jclepro.2020.125584

[5] I. Yuksel, "12—Blast-furnace slag," in *Waste and Supplementary Cementitious Materials in Concrete*, R. Siddique and P. Cachim, Eds. in Woodhead Publishing Series in Civil and Structural Engineering, Woodhead Publishing, 2018, pp. 361–415. doi: https://doi.org/10.1016/B978-0-08-102156-9.00012-2

[6] L. Wu, H. Li, H. Mei, L. Rao, H. Wang, and N. Lv, "Generation, utilization, and environmental impact of ladle furnace slag: A minor review," *Science of The Total Environment*, vol. 895, 165070, 2023.

[7] R. P. Singh, K. R. Vanapalli, V. R. S. Cheela, S. R. Peddireddy, H. B. Sharma, and B. Mohanty, "Fly ash, GGBS, and silica fume based geopolymer concrete with recycled aggregates: Properties and environmental impacts," *Constr Build Mater*, vol. 378, May 2023. doi: 10.1016/j.conbuildmat.2023.131168

[8] M. Abdalqadir, S. Rezaei Gomari, D. Hughes, A. Sidiq, and F. Shifa, "Process-based life cycle assessment of waste clay for mineral carbonation and enhanced weathering: A case study for northeast England, UK," *J. Clean Prod.*, vol. 424, Oct. 2023. doi: 10.1016/j.jclepro.2023.138914

[9] K. Elyasi Gomari, S. Rezaei Gomari, D. Hughes, and T. Ahmed, "Exploring the potential of steel slag waste for carbon sequestration through mineral carbonation: A comparative study of blast-furnace slag and ladle slag," *J. Environ. Manage*, vol. 351, 119835, 2024. doi: https://doi.org/10.1016/j.jenvman.2023.119835

[10] J. Migunthanna *et al.*, "Simplified life cycle analysis for rigid pavements constructed using waste materials as binders in concrete," *International Journal of Student Project Reporting*, vol. 1, no. 2, pp. 143–165, 2022.

[11] Z. Qiu *et al.*, "Effect of Portland cement on the properties of geopolymers prepared from granite powder and fly ash by alkali-thermal activation," *Journal of Building Engineering*, vol. 76, Oct. 2023. doi: 10.1016/j.jobe.2023.107363