



LIFE CYCLE ASSESSMENT OF GGBS–FLY ASH GEOPOLYMER CONCRETE INCORPORATING CERAMIC WASTE POWDER

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Abstract

The environmental burden associated with ordinary Portland cement (OPC) production has encouraged the development of alternative binders that use industrial and construction wastes. This study evaluates the environmental profile of M40-grade geopolymer concrete (GPC) produced using ground granulated blast-furnace slag (GGBS), fly ash (FA), and ceramic waste powder (CWP). CWP was used to replace 10%, 15%, and 20% of the fly-ash fraction in a binder containing 50% GGBS, while the activator-to-binder ratio was maintained at 0.40. A cradle-to-gate life cycle assessment (LCA) was modelled in SimaPro using the ReCiPe Midpoint (H) method. The functional unit was taken as 1 m³ of concrete. The reported global warming results were approximately 216, 215, 192, and 192 kg CO₂ equivalent for the control, 10%, 15%, and 20% CWP mixes, respectively. Thus, the 15% and 20% CWP mixes showed about an 11% lower reported global-warming result than the control mix. Across the wider set of midpoint indicators, the reported results also showed changes in ecotoxicity, toxicity, resource scarcity, land use, water consumption, ozone depletion, particulate formation, acidification, and eutrophication. The mechanical results in the source project, however, decreased as CWP replacement increased. The 10% CWP mix was identified in the source study as the preferred compromise between mechanical performance and environmental benefit. Because the available project report does not provide a complete inventory, detailed impact-category units, uncertainty analysis, or a fully documented OPC comparator, the findings should be interpreted as a

comparative screening assessment rather than a fully reproducible comparative LCA.

Keywords: life cycle assessment; geopolymer concrete; ceramic waste powder; fly ash; GGBS; SimaPro; ReCiPe Midpoint; global warming potential

1. Introduction

Concrete is essential to modern infrastructure, but conventional concrete relies heavily on Portland cement, whose manufacture is energy-intensive and releases substantial greenhouse-gas emissions. Reducing cement demand and improving the use of industrial by-products are therefore important strategies for lowering the environmental footprint of construction materials.

Geopolymer concrete is produced by activating aluminosilicate-rich precursors with alkaline solutions, commonly sodium hydroxide and sodium silicate. Fly ash and GGBS are frequently used as precursors. Their combined use can support strength development while reducing reliance on Portland cement. A further opportunity is to incorporate ceramic waste powder, which may otherwise be disposed of in landfills. Reusing this material can support waste diversion and circular material use, although the environmental benefit depends on processing requirements, transport distances, activator demand, and the resulting concrete performance.

Life cycle assessment provides a structured approach for evaluating environmental burdens associated with materials and processes. Under ISO 14040 and ISO 14044 principles, an LCA defines the goal and scope, compiles a life cycle inventory, evaluates potential impacts, and interprets the results. For geopolymer systems, the alkaline activators can be important contributors to several impact categories, so the removal of cement does not automatically mean

that every environmental indicator will improve.

The present paper focuses on the LCA component of a project that developed M40-grade GGBS-fly ash geopolymer concrete containing 10%, 15%, and 20% CWP as a replacement for part of the fly ash. The aim is to compare the reported cradle-to-gate impacts of these mixes and discuss the environmental-mechanical trade-off relevant to selecting a practical CWP replacement level.

2. Literature Review

Previous research discussed in the source project supports the use of ceramic waste and blended aluminosilicate precursors in alternative concrete systems. Bhavsar and Panchal (2022) are reported to have found that ceramic waste powder can be incorporated into geopolymer materials while maintaining broadly comparable compressive strength and potentially improving tensile strength and stiffness. Alnour et al. (2021) examined ceramic powder in conventional concrete and reported that most investigated mixes retained strength close to the control, while a high replacement level showed a small reduction.

Research on blended fly ash and GGBS systems has highlighted the complementary role of the precursors: fly ash contributes aluminosilicate content, while calcium-rich GGBS can promote earlier reaction and strength development. The source project also cites a comparative LCA

study by Xiaoshuangshi et al. (2021), reporting a potential reduction in CO₂ emissions of up to 62.73% for fly-ash-based geopolymer concrete relative to OPC concrete. Such reductions are dependent on system boundaries, precursor allocation, activator formulation, energy sources, transport, and the concrete strength used for comparison.

Studies reviewed in the project further indicate that ceramic powder performance depends on its reactivity and the presence of more reactive materials such as slag. The current study adds a mix-level comparison of environmental indicators for a constant 50% GGBS fraction and increasing CWP replacement of the fly-ash fraction. A key limitation in the wider literature, and in the project data available here, is the need for transparent reporting of inventory assumptions and impact-category units to allow independent reproduction.

3. Materials and Methods

3.1 Goal and scope

The goal was to compare the cradle-to-gate environmental impacts of four M40-grade geopolymer concrete mixes: a control mix with 50% GGBS and 50% fly ash, and three mixes in which 10%, 15%, or 20% of the fly-ash fraction was replaced by CWP. The source report identifies SimaPro as the LCA software and ReCiPe Midpoint (H) as the impact-assessment method. The stated functional unit for comparison is 1 m³ of concrete.

3.2 Mixes assessed

Mix ID	Binder composition	CWP replacement basis
GPC-Control	50% GGBS + 50% FA	0%
GPC-CWP10	50% GGBS + 40% FA + 10% CWP	10% of FA fraction
GPC-CWP15	50% GGBS + 35% FA + 15% CWP	15% of FA fraction
GPC-CWP20	50% GGBS + 30% FA + 20% CWP	20% of FA fraction

3.3 Materials and inventory boundary

The concrete system comprised fly ash, GGBS, ceramic waste powder, fine aggregate, coarse aggregate, sodium hydroxide, sodium silicate, water, and superplasticizer. The source mix design used a binder content of 400 kg/m³ and an activator-to-binder ratio of 0.40. The binder was split equally between GGBS and fly ash in the control mix; CWP replaced part of the fly ash in the other mixes. The LCA boundary was

described as cradle-to-gate, representing upstream material supply and concrete production up to the factory gate. The report describes inputting material quantities and associated processes into SimaPro.

The source document does not provide a complete, auditable life cycle inventory table for every mix, including all transport distances, electricity and fuel consumption, allocation rules for by-products, or the exact database process identifiers. Consequently, these

parameters cannot be independently checked from the report and should be supplied in a final journal submission.

3.4 Impact assessment and interpretation

The study used ReCiPe Midpoint (H). The reported indicators cover global warming, terrestrial ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, fossil resource scarcity, stratospheric ozone depletion, ozone formation, fine particulate matter formation, terrestrial acidification, freshwater and marine eutrophication, ionizing radiation, freshwater and marine ecotoxicity, land use, mineral resource scarcity, and water consumption. Results were compared between mixes as reported in the project graphs. Since units for several plotted categories are not

legible in the report text extraction, this paper avoids assigning unverified units to those indicators.

4. Results and Discussion

4.1 Global warming potential

The project graphs report global-warming results of approximately 216, 215, 192, and 192 for the control, 10% CWP, 15% CWP, and 20% CWP mixes, respectively. The project conclusion describes these results as kg CO₂ equivalent. Relative to the control, the 10% CWP mix showed a reduction of about 0.5%, while the 15% and 20% mixes showed reductions of about 11.1%. The difference between the 15% and 20% mixes was negligible in the reported global-warming result.

Mix	Reported GWP	Change vs. control	Interpretation
Control (0% CWP)	216	Reference	Highest reported GWP
10% CWP	215	-0.5%	Small GWP reduction
15% CWP	192	-11.1%	Lower reported GWP
20% CWP	192	-11.1%	Similar GWP to 15% CWP

These values suggest that replacing part of the fly ash with CWP reduced the reported global-warming indicator at 15% and 20% replacement. This trend should not be interpreted as proof that CWP always has a lower carbon footprint than fly ash: the result depends on how waste materials are allocated, the processing needed to produce CWP, transport, and the background datasets selected in SimaPro. Those assumptions should be explicitly documented.

4.2 Other midpoint impact categories

The source graphs show relatively small differences between the four mixes for several indicators, while some categories vary more visibly. In the graph for terrestrial ecotoxicity, the reported values decrease from approximately 1.76×10^3 for the control to approximately 1.17×10^3 for the CWP mixes; the extracted graph does not clearly distinguish all three CWP values. The plotted human toxicity and fossil-resource-scarcity indicators also decrease with CWP replacement. In the second and third graphs, the values for ozone depletion, ozone formation, particulate formation, acidification, eutrophication, ionizing radiation, ecotoxicity, land use, mineral resource scarcity, and water consumption vary by mix. The source graphs show modest

improvements in some indicators at higher CWP contents, but the absence of clearly stated units and complete numeric tables prevents a robust category-by-category statistical comparison.

A key LCA implication is that environmental performance is multi-dimensional. A mix that reduces global warming may not improve every toxicity, resource, or water-related indicator by the same proportion. This is particularly relevant for geopolymers because sodium hydroxide and sodium silicate production can contribute materially to the environmental profile. Future optimization should therefore consider the full midpoint profile rather than carbon emissions alone.

4.3 Relationship between environmental impact and mechanical performance

The source project reports that 28-day compressive strength ranged from 43.57 to 51.21 MPa across the investigated mixes. The reported split tensile strength decreased from 3.38 MPa for the control to 3.07, 2.73, and 2.50 MPa as CWP replacement increased from 10% to 20%. Flexural strength was reported as 3.97 MPa for the control and approximately 3.59, 3.50, and 3.35 MPa for the 10%, 15%, and 20% CWP mixes, respectively. These results indicate that higher CWP replacement reduced the

reported tensile and flexural performance, even though the LCA graphs indicate lower global-warming results at 15% and 20% replacement. The project identified 10% CWP as the preferred replacement level when mechanical performance and sustainability were considered together. This is a multi-criteria selection rather than the mix with the lowest reported global-warming result. Before making a structural recommendation, the strength values and the stated acceptance criteria should be checked against the original laboratory records; the project report contains some inconsistencies in its tables and narrative, including a flexural-strength average that does not match the listed specimen values.

4.4 Comparison with OPC concrete and study limitations

The project introduction and conclusion state that geopolymer concrete can reduce environmental impacts relative to conventional OPC concrete. However, the numerical LCA graphs reproduced in the source report compare the four geopolymer mixes with one another; a complete OPC M40 inventory and corresponding numerical impact results are not provided in the available tables. Therefore, this paper does not calculate a percentage reduction relative to OPC. A defensible OPC comparison would require equivalent functional performance, consistent system boundaries, the same impact-assessment method, transparent material and transport inventories, and clear allocation rules for fly ash, GGBS, and CWP. Other limitations are the absence of a full inventory table, database and process version details, sensitivity and uncertainty analyses, and clear units for all plotted midpoint categories. In addition, the report describes the boundary as cradle-to-gate; service life, maintenance, demolition, and end-of-life benefits are outside the assessed boundary. Accordingly, the present findings should be viewed as preliminary comparative results for the four geopolymer mixes.

5. Conclusions

1. A cradle-to-gate LCA of four GGBS–fly ash geopolymer concrete mixes containing 0%, 10%, 15%, and 20% CWP was reported using SimaPro and ReCiPe Midpoint (H).
2. The reported global-warming values were approximately 216, 215, 192, and 192 kg

CO₂ equivalent for the control, 10%, 15%, and 20% CWP mixes. On this basis, the 15% and 20% mixes showed about an 11% lower result than the control, while the 10% mix showed only a small reduction.

3. The environmental profile was not represented by global warming alone. The source graphs included toxicity, ecotoxicity, ozone-related, particulate, acidification, eutrophication, radiation, land-use, mineral-resource, and water-consumption indicators; clearer numerical reporting is needed to compare these categories reliably.
4. Increasing CWP replacement was accompanied by lower reported split tensile and flexural strengths. The source project selected 10% CWP as the best overall compromise between mechanical performance and environmental considerations.
5. A quantitative claim of environmental superiority over OPC concrete cannot be verified from the numerical results supplied in the report because a complete OPC comparator is not documented. Future work should report the complete life cycle inventory, impact-category units, allocation assumptions, sensitivity analysis, and a functionally equivalent OPC benchmark.

Data availability statement

The data discussed in this paper were extracted from the supplied undergraduate project report. The complete SimaPro model, process-level inventory, database version, and full numerical impact tables were not included in the supplied document and should be made available by the authors if required by the target journal.

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