



Life Cycle Assessment of Geopolymer concrete with various precursors

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Abstract

The production of cement used in conventional concrete is contributing to approximately 8% of the global carbon dioxide emissions. There is a necessity to address this issue and develop sustainable construction materials. This study evaluates the impact caused by the production of materials used in conventional concrete of M40 grade and also the impact caused by the geopolymer concrete (GPC) of M40 grade. The geopolymer concrete used in this study is made using fly ash, ground granulated blast furnace slag (GGBS) and metakaolin as primary binder materials. The aim is to evaluate the feasibility of GPC as a low-carbon alternative to Ordinary Portland Cement (OPC) concrete by comparative Life Cycle Assessment (LCA). The LCA is carried out as per the ISO 14040 and ISO 14044 guidelines by using SimaPro software. Simapro software uses the Ecoinvent database to evaluate the impact caused by various processes on the environment. To find the impact of the materials used in the study the functional unit of 1 m³ of concrete is used, and the assessment is carried out from cradle-to-gate. The impact of the materials is assessed on the key categories, which include global warming potential (GWP), ozone depletion, acidification, eutrophication, and human toxicity, by using the ReCiPe Midpoint (H) method. The results show that geopolymer concrete production reduced the impact on the environment compared to OPC concrete. The impact of GWP is reduced by 41-45 percent, demonstrating the effectiveness of GPC in lowering carbon emissions. These findings highlight the potential of geopolymer concrete as a sustainable construction material and support its adoption in eco-friendly infrastructure development.

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Keywords: Geopolymer concrete · Fly ash · GGBS · Life cycle assessment · Sustainability · Carbon emissions · Environmental impact

Introduction

Concrete is the most widely used construction material worldwide, with an annual production exceeding 4.4 billion tonnes and expected to reach approximately 5.5 billion tonnes by 2050 [1]. Despite its extensive use, Ordinary Portland Cement Concrete (OPCC) is a major contributor to environmental concerns, accounting for nearly 5–8% of global CO₂ emissions [2]. This is mainly due to the manufacturing process of cement which is energy-intensive, majorly calcination process, which releases high quantities of greenhouse gases. Due to this development of sustainable concrete using alternate binders, supplementary cementitious materials and usage of bi products from industries has become a challenging research topic [3].

Sustainable concrete is the concrete that is produced with materials that maintain structural performance by reducing environmental impacts throughout their lifecycle [4]. In this situation, Geopolymer Concrete (GPC) has evolved as a promising alternative to ordinary Portland cement concrete. GPC relies on industrial by-products such as fly ash (FA), ground granulated blast furnace slag (GGBS), and rice husk ash (RHA) as precursors rather than portland cement concrete [5]. The production of GPC significantly reduces carbon emissions compared to ordinary Portland cement, by about 80 percent based on the previous studies [6]. GPC also exhibits comparable to or better than OPCC, mechanical and durability properties which includes improved resistance to sulphate attack, chloride ingress, and elevated temperatures [7].

However, the performance and sustainability of GPC depend strongly on mix design optimization, particularly the type and dosage of alkaline activators [8]. Life Cycle Assessment (LCA) is used to evaluate the impacts caused by the construction materials from their extraction to the production of concrete on the environment [9]. The life cycle assessment is carried out using the standard frameworks such as ISO 14040 and ISO 14044 to assess the impact on some of the key categories such as Global Warming Potential (GWP), energy consumption, and resource depletion [10]. Sustainable assessment of concrete also includes economic and social considerations [11].

The incorporation of alternative cementitious materials further improved the sustainability. The partial replacement of cement with agricultural and industrial wastes such as pistachio shells, rice husk ash and waste gypsum boards in concrete, produced low density concrete and enhanced the sustainability of concrete [12], [13]. Mineral admixtures like Fly Ash, GGBS, metakaolin, and silica fume not only increased the durability but also reduce cement consumption and associated emissions [14]. Environmental factors, particularly temperature variations, influence pavement performance, accelerating deterioration and increasing maintenance requirements [15].

Various LCA methodologies, including the ReCiPe approach, have been applied to compare environmental impacts of construction materials and structural systems [16]. These studies consistently identify cement production as the dominant contributor to environmental impact, followed by transportation and raw material processing [17]. Advances in alternative cement technologies and efficient material usage are therefore essential for sustainable development in the construction sector.

Building upon these findings, the present study conducts a comparative cradle-to-gate LCA of M40-grade OPCC and G40-grade GPC. The geopolymer mixes incorporate FA and GGBS as precursors, with sodium silicate (SS) and sodium hydroxide (SH) serving as alkaline activators. The analysis is performed using SimaPro software integrated with the Ecoinvent database, applying the ReCiPe 2016 Midpoint (H) V1.08 / World (2010) methodology to evaluate environmental impact categories such as GWP and resource depletion [18]. Unlike previous studies, this research not only compares concretes of equivalent grades but also investigates the influence of varying SS and SH proportions on environmental performance. Particular attention is given to sodium silicate production, which involves energy-intensive processes. This detailed assessment provides deeper insights into environmental trade-offs and supports the adoption of geopolymer concrete as a sustainable alternative.

Literature Review

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts of materials and systems throughout their entire life cycle, from raw material extraction to final disposal. It provides a comprehensive framework for quantifying energy consumption, emissions, and resource utilization. The methodology is standardized under ISO 14040 and ISO 14044, which define four key phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [19], [20]. These standards ensure consistency and comparability in environmental evaluations.

In the construction industry, LCA has gained increasing importance due to growing concerns about environmental sustainability. The life cycle assessment of concrete has been extensively carried out as it is the most widely used construction material and cement used in concrete is the major contributor of the global CO₂ emissions. Cement

manufacturing contributes to the major global CO₂ emissions, which made it essential to search for more sustainable alternatives [21].

Geopolymer concrete (GPC) has emerged as a viable alternative to OPC-based concrete and has been widely assessed using LCA methodologies. Research indicates that GPC can significantly reduce global warming potential (GWP), with reductions typically ranging from 40% to 60% compared to conventional concrete, depending on mix composition and system boundaries [22]. However, LCA studies also reveal that while GPC reduces greenhouse gas emissions, it may increase impacts in other categories such as human toxicity and ecotoxicity. These impacts are primarily associated with the production of alkaline activators such as sodium hydroxide and sodium silicate [22], [23].

The environmental performance of geopolymer concrete is influenced by several parameters, including raw material sourcing, transportation, curing conditions, and energy consumption. Among these, the production of alkaline activators has been identified as a key contributor to environmental impacts. Studies have shown that sodium silicate production is particularly energy-intensive and can offset some of the environmental benefits of eliminating cement [23]. Similarly, the production route and source of sodium hydroxide significantly influence LCA outcomes, highlighting the importance of regional data and manufacturing processes [24].

Mix design optimization plays a crucial role in improving both the mechanical performance and environmental sustainability of geopolymer concrete. Studies on fly ash-based GPC demonstrate that parameters such as sodium hydroxide molarity, sodium silicate-to-sodium hydroxide ratio, and solution-to-binder ratio significantly affect environmental impacts [25]. Therefore, optimizing mix proportions is essential for achieving a balance between structural performance and reduced environmental footprint.

LCA has also been widely used to evaluate the incorporation of recycled materials and industrial by-products in concrete. Materials such as fly ash, ground granulated blast furnace slag (GGBS), and recycled aggregates have been shown to reduce energy consumption, greenhouse gas emissions, and natural resource depletion [26]. Comparative studies consistently indicate that the use of such materials enhances sustainability without compromising performance.

Advanced impact assessment methods, including ReCiPe, CML, and TRACI, are commonly employed in LCA studies to quantify environmental impacts across multiple categories such as climate change, human health, and ecosystem quality [27]. Among these, the ReCiPe method is widely used due to its comprehensive framework and ability to integrate midpoint and endpoint indicators.

Despite its advantages, LCA faces several limitations. Data availability and quality remain major challenges, as accurate life cycle inventory data are often difficult to obtain. Additionally, variations in system boundaries, allocation procedures, and methodological assumptions can lead to inconsistencies in results across different studies [28]. These challenges emphasize the need for standardized databases and improved methodological practices.

Overall, LCA serves as a powerful decision-making tool for evaluating and improving the environmental performance of construction materials. It helps identify key contributors to environmental impacts and supports the development of sustainable solutions such as geopolymer concrete. As environmental concerns continue to grow, LCA will play an increasingly important role in guiding sustainable construction practices.

Raw Materials

The primary raw materials used in this study are fly ash (FA), ground granulated blast furnace slag (GGBS), and metakaolin (MK), which are used as precursors in the production of geopolymer concrete (GPC). Fly ash, a by-product obtained from coal based thermal power plants, is rich in silica and alumina, is procured from Raamagundam thermal power station. GGBS, byproduct of the iron and steel industry, contains a significant amount of calcium, silica and alumina which contributes to improved strength development and durability characteristics. Metakaolin, a highly reactive pozzolanic material produced by the calcination of kaolin clay, enhances early strength and refines the microstructure of geopolymer systems due to its high alumina content [29], [38].

sodium silicate (SS) and sodium hydroxide (SH) are used as alkaline activators to activate the precursors and which in turn undergoes geopolymerization process. The major composition that plays crucial role in the polymerization process and in determining the mechanical performance and durability of geopolymer concrete is the ratio of silica (SiO₂) to sodium oxide (Na₂O) in the activator solution. [30]. Based on the trial mix data conducted to achieve G40 grade concrete, an alkaline binder ratio of 0.4 was selected. Two different mixes were prepared by varying the Na₂O content to 5% and 6%, respectively.

The fly ash used in this investigation was obtained from a thermal power plant in Ramagundam, India. It is classified as Class F fly ash, derived from bituminous coal combustion, and complies with IS 3812 (Part 1): 2013 specifications for use as a pozzolanic material in concrete [31]. GGBS was sourced from the Visakhapatnam Steel Plant and meets the requirements of IS 12089: 2015. Metakaolin used in this study is a commercially available processed material with high fineness and reactivity, commonly used to improve strength and durability in cementitious systems [38]. The particle size distribution for FA ($D_{10} = 5 \mu\text{m}$, $D_{50} = 25 \mu\text{m}$, $D_{90} = 60 \mu\text{m}$) and GGBS ($D_{10} = 8 \mu\text{m}$, $D_{50} = 30 \mu\text{m}$, $D_{90} = 65 \mu\text{m}$) indicates their suitability for geopolymer applications.

A sulphonated naphthalene-based superplasticizer was incorporated to improve workability without increasing water content, conforming to IS 9103: 1999 [33]. Manufactured sand (M-sand), used as fine aggregate, complies with IS 383:1970 and falls within Zone II grading. Coarse aggregates consisting of crushed granite with a nominal size of 20 mm were used, also conforming to IS 383:1970, making them suitable for structural applications [34].

Functional Unit

The Life Cycle Assessment (LCA) is carried out for a functional unit of 1 m^3 of concrete. In this life cycle analysis all the raw materials required for the production of are included, along with transportation from nearby sources. A comparative analysis is performed between M40 grade Ordinary Portland Cement Concrete (OPCC) and two G40 grade geopolymer concrete mixes. The evaluation is conducted using SimaPro software in accordance with ISO 14040 and ISO 14044 standards [19], [20].

System Boundaries

A cradle-to-gate system boundary is adopted for this study, considering all processes from raw material extraction to concrete production. The system includes manufacturing of raw material, transportation of raw materials from the nearest source to the casting yard, energy and electricity consumption, water usage, and emissions to air, water, and land. A comprehensive evaluation of the impact caused to the environment due to the production of concrete is carried out [35].

Life Cycle Inventory (LCI)

The life cycle inventory includes all relevant inputs and processes involved in the production of OPCC and GPC. For M40 grade OPCC, the primary materials considered are cement, fine aggregate (Robo sand), and coarse aggregate. Cement production data is obtained from the Ecoinvent database under the “market for cement, Portland” dataset. Aggregates are treated as natural resource inputs within the database [36].

Sodium silicate (SS), used as an activator, is assumed to be produced from sodium hydroxide (SH), with data sourced from the Ecoinvent database. In this study, fly ash and GGBS are treated as industrial by-products and assigned zero environmental burden based on the cut-off approach [36]. Metakaolin, however, is a processed material and its production involves calcination, which contributes to environmental impacts and is therefore included in the inventory [38].

The production of sodium hydroxide is identified as a major contributor to environmental impacts. SH is produced through the chlor-alkali process, which includes membrane, diaphragm, and mercury cell technologies. The membrane cell method is considered in this study due to its relatively lower energy consumption and improved environmental performance [37]. It is reported that approximately 209 kg of sodium hydroxide is required to produce 1000 kg of sodium silicate solution with 48% solids [17].

Transportation

The movement of raw materials from their sources to the concrete production facility is modeled to reflect real-world construction practices. For the purpose of this study, the mixing unit is assumed to be situated at the same location as the laboratory, ensuring consistency in analysis. The distances between the material sources and the production site are estimated using digital mapping tools to obtain realistic transport routes.

All raw materials are considered to be transported using heavy-duty trucks, which are commonly employed in construction logistics. The environmental impacts associated with transportation are calculated based on the quantity of materials and corresponding freight distances. Standardized transportation datasets are adopted from the Ecoinvent database to maintain accuracy and reliability in the life cycle assessment [36].

Cement is assumed to be delivered from the nearest production facility located approximately 300 km from the mixing site. Both fine and coarse aggregates are obtained from a quarry situated at a distance of around 10 km. Fly ash is sourced from the Ramagundam thermal power plant, while GGBS is transported from the Visakhapatnam steel plant, representing the closest industrial suppliers. Metakaolin, being a processed material, is assumed to be procured from a regional supplier, with transportation distance estimated based on availability [38].

In addition to transportation, the consumption of energy and water during concrete production is also considered. The electricity required for producing 1 m³ of concrete is taken as 5.55 kWh, which accounts for mixing and associated operations. Water usage involved in the process is also included in the inventory. Both energy and water data are derived from the Ecoinvent database to ensure consistency in environmental impact evaluation [36].

Results and Discussion

The results clearly indicate that geopolymer concrete (GPC) exhibits significantly lower global warming potential compared to ordinary Portland cement concrete (OPCC). OPCC shows a CO₂ emission of 390 kg CO₂ eq, whereas GPC with GGBS-Metakaolin and GGBS-Flyash shows 210 kg CO₂ eq and 187 kg CO₂ eq respectively, indicating a reduction of approximately 46–52%.

In categories such as ozone formation, terrestrial acidification, freshwater eutrophication, and marine eutrophication, GPC mixes consistently perform better than OPCC. This improvement is primarily due to the elimination of Portland cement and the use of industrial by-products such as fly ash and GGBS.

Table 5.1: Process Inventory

No	Process	Unit	OPCC	GPC (GGBS-Metakaolin)	GPC (GGBS-Flyash)
1	Alkali activators	kg	x	158	158
2	Cement transport	kg	350	x	x
3	Portland cement	kg	350	x	x
4	Coarse aggregate	kg	1.23	1.23	1.23
5	Fine aggregate	kg	685	685	685
6	Fly ash with transport	kg	x	x	150
7	GGBS transport	kg	x	150	150
8	GGBS	kg	x	150	150
9	Heat (natural gas)	MJ	x	375	x
10	Kaolin	kg	x	150	x
11	Metakaolin	kg	x	150	x
12	Sodium hydroxide	kg	x	9.6	9.6
13	Sodium silicate	kg	x	74.4	74.4
14	Water	kg	158	610	610
15	Transport EURO3	tkm	x	98.6	138
16	Transport EURO6	tkm	105	x	x

Table 5.2: Impact Assessment Results

Impact category	Unit	OPCC	GPC (GGBS-Metakaolin)	GPC (GGBS-Flyash)
Global warming	kg CO ₂ eq	390	210	187
Stratospheric ozone depletion	kg CFC11 eq	5E-5	9.02E-5	7.9E-5
Ionizing radiation	kBq Co-60 eq	2.15	11	7.81
Ozone formation (human health)	kg NO _x eq	0.956	0.71	0.753
Fine particulate matter	kg PM _{2.5} eq	0.331	0.346	0.315
Ozone formation (terrestrial)	kg NO _x eq	0.981	0.734	0.777
Terrestrial acidification	kg SO ₂ eq	0.758	0.729	0.672
Freshwater eutrophication	kg P eq	0.0796	0.0629	0.053
Marine eutrophication	kg N eq	0.00698	0.00596	0.00559
Terrestrial ecotoxicity	kg 1,4-DCB	1.06E3	1.4E3	1.53E3
Freshwater ecotoxicity	kg 1,4-DCB	5.2	9.32	8.84
Marine ecotoxicity	kg 1,4-DCB	7.48	12.7	12.2
Human carcinogenic toxicity	kg 1,4-DCB	10.1	12.8	12.7
Human non-carcinogenic toxicity	kg 1,4-DCB	176	216	207
Land use	m ² a crop eq	12.5	5.58	5.44
Mineral resource scarcity	kg Cu eq	0.609	0.707	0.703
Fossil resource scarcity	kg oil eq	62.1	57.7	51.3
Water consumption	m ³	0.575	2.69	2.22

However, certain impact categories such as terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and human toxicity are higher in GPC mixes. This is mainly attributed to the production and use of alkaline activators like sodium hydroxide and sodium silicate, which have higher environmental burdens.

Water consumption is also significantly higher in GPC mixes compared to OPCC, with values of 2.69 m³ and 2.22 m³ for GGBS-Metakaolin and GGBS-Flyash respectively, compared to 0.575 m³ for OPCC. Fossil resource scarcity is lower in GPC mixes, indicating reduced dependence on fossil fuels.

Conclusions

Geopolymer concrete demonstrates substantial environmental benefits over OPCC, particularly in reducing global warming potential. The use of industrial by-products such as fly ash and GGBS significantly contributes to sustainability. GPC mixes show improved performance in most impact categories related to emissions and resource depletion. Higher toxicity-related impacts in GPC highlight the need for optimization in alkaline activator usage. Among the two GPC mixes, GGBS-Flyash performs slightly better than GGBS-Metakaolin in most environmental categories. Despite some drawbacks, GPC can be considered a sustainable alternative to conventional concrete for construction applications.

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