

# A review of the life cycle assessment of geopolymer concrete

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**Abstract.** Geopolymer concrete (GPC) has emerged as a promising alternative to Portland cement concrete (PCC), offering a lower carbon footprint, superior performance, and enhanced resource efficiency. It is synthesized from aluminosilicate industrial byproducts, including fly ash (FA), ground granulated blast-furnace slag (GGBFS), metakaolin (MK), and rice husk ash (RHA). When activated by alkaline solutions, these precursors form a three-dimensional amorphous network, eliminating the need for energy-intensive clinker firing. This review systematically evaluates the life cycle assessment (LCA) of GPC and compares its environmental performance with that of PCC. Several factors strongly influence the LCA outcomes of GPC. Alkaline activators, particularly sodium silicate ( $\text{Na}_2\text{SiO}_3$ ), are identified as primary contributors to global warming potential, human toxicity, and resource depletion. Precursor selection also plays a decisive role. High-calcium materials such as GGBFS yield superior strength with relatively lower impacts, while MK-based systems may result in higher overall burdens due to their elevated  $\text{Na}_2\text{SiO}_3$  demand. Curing regimes further affect the sustainability profile, as high-strength mixtures often require high-temperature curing, introducing additional trade-offs compared with ambient curing used in PCC. Moreover, transportation of raw materials, especially regionally constrained components like  $\text{Na}_2\text{SiO}_3$  and MK, significantly adds to the environmental footprint. Despite these insights, current studies remain limited, as most LCAs only adopt cradle-to-gate boundaries and overlook use-phase and end-of-life scenarios. This review identifies key research gaps and proposes future directions, including the development of low-impact activators, ambient curing strategies, and integration of durability and circular economy principles into LCA frameworks to advance sustainable GPC deployment.

**Keywords:** geopolymer concrete, life cycle assessment, alkaline activator, strength, transportation.

## 1. Introduction

Concrete is the most widely used construction material globally. As its primary binding component, cement strengthens and enables structural elements to carry applied loads [1]. However, the production of OPC imposes substantial environmental burdens due to considerable greenhouse gas (GHG) emissions, particularly carbon dioxide ( $\text{CO}_2$ ). Recent studies report that approximately 0.8-0.9 tons of  $\text{CO}_2$  are emitted per ton of cement produced [2], with the industry accounting for an estimated 6%-8% of global  $\text{CO}_2$  emissions [3]. These high emissions mainly result from the energy-intensive and carbon-intensive clinker calcination process. In response to global carbon reduction targets and circular economy policies, developing low-carbon binder systems capable of replacing OPC has become a central focus in concrete technology research.

GPC has emerged as a promising alternative due to its three advantages: low carbon, high performance, and resource efficiency. GPC is synthesized from rich aluminosilicate industrial byproducts, such as fly ash, slag, metakaolin, and rice husk ash, which serve as precursors. These materials form a three-dimensional amorphous network through alkali-activated polymerization, eliminating the need for traditional clinker firing. Additionally, GPC exhibits rapid strength development, high-temperature resistance, and excellent durability against sulfate attack and chloride penetration, and has been successfully demonstrated in structural elements such as railway sleepers and sewer pipes, marine concrete, repair of highways, and porous thermal insulation panels [4].

Motivated by sustainability considerations, researchers have increasingly compared the environmental impacts of GPC and PPC. This comparison aims to identify more sustainable alternatives and quantify potential reductions in carbon footprints across different construction applications. Life cycle assessment is a powerful tool for quantifying, evaluating, comparing, and

improving the environmental performance of products throughout their life cycle [5]. It has been widely applied due to its ability to capture direct and indirect environmental impacts, from raw material extraction to manufacturing, use, and end-of-life management. Systematic evaluation of GPC's environmental performance is of considerable scientific and policy significance. It helps inform policymakers, engineers, and industry stakeholders about best practices in material selection and sustainable construction design. This review addresses key factors influencing the LCA of GPC, including the type and dosage of alkaline activators, the selection of solid precursors, curing processes, and transportation logistics. Each factor significantly affects energy consumption, GHG emissions, and environmental impact.

Current research gaps remain. Most existing LCA studies on GPC only consider the cradle-to-gate stage. This approach excludes the use and end-of-life phases, which may underestimate the overall environmental impacts and limit comprehensive sustainability assessments. Additionally, geography leads to substantial differences in ecological outcomes across regions and application types. Future research directions include the development of low-impact alkaline activators, ambient curing strategies, integration of durability into LCA frameworks, and adoption of circular economy principles. These measures aim to enhance resource efficiency, reduce environmental burdens, and support the long-term sustainability of the construction industry.

## 2. Research method

The research method proposed by Fink was adopted to conduct this review [6], and the reviewed bibliography articles were collected from the Web of Science, Scopus, EI Compendex, and institutional databases such as the Global Carbon Project. Multidimensional retrieval methods were conducted using keywords including geopolymer concrete, life cycle assessment, industrial byproducts, construction waste, carbon emissions, and energy consumption. After screening titles and abstracts, approximately 20 articles were selected for in-depth analysis. Based on the existing work, the selected articles were further categorized and grouped according to the key factors influencing environmental performance. Among these, alkaline activators were identified as the primary contributors. In addition, precursor selection plays a decisive role. This review summarizes the effects of precursors on the strength and environmental performance of geopolymer concrete. Compared with PPC, GPC often requires more demanding curing conditions, which impose an additional environmental burden. Moreover, due to the differing raw material sources of PCC and GPC, it is essential to analyze and compare the environmental impacts arising from transportation.

## 3. Effect of alkaline activator

Alkaline activators, mainly Sodium hydroxide (NaOH) and sodium silicate ( $\text{Na}_2\text{SiO}_3$ ), play a central role in GPC. However, alkaline activators are identified as the primary driver of GPC's environmental impacts. According to the LCA conducted by Habert et al. [7],  $\text{Na}_2\text{SiO}_3$  solution accounts for 65% of GPC's global warming potential (GWP) and 72% of its human toxicity potential, with the high energy consumption of its high-temperature melting process representing a significant environmental burden. Dal Pozzo et al. [8] further confirmed through LCA that  $\text{Na}_2\text{SiO}_3$  production contributes 57% of GPC's acidification potential and 61% of its fossil resource depletion potential. This outcome arises from the reaction between silica sand and soda ash, which requires melting at 1100-1400 °C. The process is heavily dependent on fossil fuel combustion, leading to significant emissions of  $\text{CO}_2$  and toxic by-products.

The production of NaOH also varies significantly in terms of its environmental impact, depending on raw material sources and energy structures. Salas et al. [9] compared two NaOH production pathways and found that NaOH derived from solar evaporation of seawater (Ecuador scenario) exhibits 42% lower GWP and 38% lower acidification potential than NaOH obtained via rock salt or solution mining (European scenario). The reduction is primarily attributed to avoiding energy-

intensive mining and brine extraction processes. However, the chlor-alkali process used for NaOH production increases ozone depletion potential (ODP). As noted by Salas et al., 89% of GPC's ODP originates from carbon tetrachloride used in the chlor-alkali process. Consequently, GPC exhibits an ODP that is 12 times higher than that of PCC.

Optimizing alkali activator parameters is necessary further to enhance the emission reduction potential of geopolymer concrete. The key parameters include alkali activator solution to fly ash ratio (S/F), sodium silicate to sodium hydroxide ratio (SS/SH), and NaOH concentration. Shi et al. [10], through MANOVA analysis, reported that the S/F ratio contributes up to 87.21% of CO<sub>2</sub> emissions. Specifically, when the S/F ratio increases from 0.40 to 0.52, CO<sub>2</sub> emissions per unit volume rise from 260 kg to 341 kg. The SS/SH ratio simultaneously affects both mechanical strength and environmental performance. Bajpai et al. [11] demonstrated that reducing SS/SH from 4.0 to 2.0 decreases GWP by 23%, since high-impact sodium silicate is substituted with lower-impact NaOH. However, when SS/SH falls below 1.5, the geopolymerization reaction is hindered, requiring higher NaOH concentrations to compensate, which offsets the emission savings. Shi et al. [10] identified an optimal SS/SH value of 2.0, achieving a balance between compressive strength (59.2 MPa) and CO<sub>2</sub> emissions (305 kg/m<sup>3</sup>).

Although the direct influence of NaOH concentration on CO<sub>2</sub> emissions is relatively small, it indirectly affects activator efficiency. Its contribution to CO<sub>2</sub> emissions is only 2.4% [10]. Nonetheless, concentrations below 10 mol/L reduce precursor dissolution efficiency, necessitating a higher S/F ratio, while concentrations above 14 mol/L increase brine discharge during NaOH synthesis, raising freshwater ecotoxicity by 17% [9].

#### 4. Effect of the strength

Studies have shown that GPC of different strength grades exhibits significant variations from PCC in key environmental impact categories, such as global warming potential (GWP) and aquatic and terrestrial ecotoxicity. These differences are primarily determined by the type and dosage of solid precursors, which govern strength classification and strongly influence the environmental impact profile. Common precursors include fly ash (FA), ground granulated blast-furnace slag (GGBFS), metakaolin (MK), and rice husk ash (RHA).

Martinez et al. [12] conducted a meta-analysis demonstrating that high-strength GPC mixtures, especially those incorporating GGBFS, can achieve up to 50% lower emissions than PCC. The advantage of GGBFS arises from its high calcium content and strong binding properties, which ensure excellent mechanical performance under high-strength requirements while reducing the demand for alkali activators, lowering overall environmental impacts. Similarly, Shi et al. [10] reported that GPC produces substantially lower CO<sub>2</sub> emissions than PPC of equivalent strength grades, with reductions of up to 166.36 kg/m<sup>3</sup>, approximately 62.73% of PPC emissions. In contrast, FA contributes only modestly to emission reductions, accounting for 6-10%.

Abbas et al. [13] demonstrated that metakaolin geopolymer concrete achieves a 61% reduction in GWP compared with conventional cement concrete for MK-based systems. This is mainly because clinker production requires calcination at around 1450 °C, whereas kaolin can be converted into MK at only 850 °C, significantly reducing energy consumption and heat losses. MK GPC also improved human health-related impact categories by 5.1-9.4%. Nevertheless, the overall environmental impact of metakaolin geopolymer concrete is, in fact, 68% higher than that of cement concrete. This is mainly attributed to the high content of Na<sub>2</sub>SiO<sub>3</sub>, which significantly worsens multiple impact categories, including ecotoxicity, acidification, and eutrophication, with its negative contribution accounting for up to 88%.

In addition to precursor selection, the curing regime is a critical factor affecting the performance of high-strength GPC. High-strength mixtures are particularly sensitive to curing conditions, as elevated temperatures can accelerate geopolymerization and enhance 28-day compressive strength [14]. Compared with PPC, mixtures require curing at 60-80 °C for 24 hours to achieve strength levels

[15]. However, such high-temperature curing contributes 39.97 kg CO<sub>2</sub>-eq/m<sup>3</sup>, accounting for 12.4% of total emissions, whereas OPC curing at ambient conditions generates negligible CO<sub>2</sub> [16]. These findings emphasize the importance of carefully balancing mechanical performance and environmental impact when designing high-strength GPC.

## 5. Effect of transportation

Previous studies have shown that cement production imposes substantial environmental impacts in PPC due to the consumption of raw materials such as limestone and clay and fuel use, which account for the largest share of the environmental burden [17]. Raw material transportation is considered the second most significant environmental burden after cement production [18,19]. Accordingly, assessing and comparing the transportation-related impacts of GPC and PPC is essential. Nguyen et al. [19] analyzed 134 potential transportation routes from raw material sources to their destinations, excluding outliers. Their results indicated that OPC had the lowest transportation emissions, primarily because most of its raw materials were locally sourced.

In contrast, blended cements such as silicate composite cement (SC) and fly ash cement (FAC) showed moderate transportation emissions, as additional transport of FA or GGBFS to cement plants was required. Given the relative scarcity of slag, transport distances were typically longer. Metakaolin-based geopolymer (MKG) and high-volume limestone alkali-activated slag cements (HLAASC) exhibited the highest and most variable transportation emissions and energy use, largely because their key components, particularly sodium silicate and sodium carbonate, are produced in geographically concentrated locations. Although MKG effectively reduces GHG emissions, its practical use in North America is limited by resource scarcity and high supply costs. Similarly, Munir et al. [20] emphasized that utilizing locally available industrial byproducts in GPC production can significantly reduce both carbon emissions and the costs associated with long-distance transportation. For instance, bark boiler ash, construction and demolition waste (CDW), mine tailings, and fiber waste are common industrial byproducts in Finland's South Karelia region, typically disposed of by landfilling. However, these materials can be repurposed as fillers or binding agents in GPC. In LCA calculations, such industrial byproducts are classified as waste, with their environmental burdens assigned as zero, while only the energy required for pretreatment is considered. This energy demand is minimal; for example, CDW requires only 27.6 kWh per ton [19].

## 6. Future Outlooks

Significant knowledge gaps remain despite the growing number of LCA studies on GPC. Most assessments focus on cradle-to-gate boundaries, often overlooking use-phase performance and end-of-life scenarios. Moreover, regional variations in energy infrastructure, material availability, and waste streams are underexplored, and comprehensive databases for emerging precursors and alternative activators remain limited.

Future research should focus on developing low-impact activators, strategies for ambient-temperature curing, incorporating durability into LCA frameworks, and integrating circular economy principles such as repurposing industrial byproducts. Dynamic LCA approaches and scenario analysis can improve predictive accuracy and support decision-making for sustainable GPC deployment. Addressing these aspects will enhance both the practical relevance and environmental credibility of GPC, supporting its adoption as a sustainable construction material.

## 7. Conclusions

This review systematically summarizes the LCA of GPC and evaluates its environmental performance relative to PCC. GPC demonstrates substantial potential to reduce greenhouse gas emissions. However, its environmental benefits are highly sensitive to key parameters, including alkaline activator type and dosage, solid precursor selection, curing regimes, and transportation

logistics. The interactions among these factors can further amplify or offset environmental impacts, emphasizing the need for integrated design and optimization. Among these, alkaline activators, particularly  $\text{Na}_2\text{SiO}_3$ , are identified as the primary contributors to GPC's environmental impacts, affecting multiple categories including global warming potential, human toxicity, and resource depletion. Optimizing the sodium silicate to sodium hydroxide ratio and the alkali activator solution to fly ash ratio is critical to balance mechanical performance with environmental efficiency.

The choice of precursor also plays a decisive role. High-calcium materials like GGBFS provide high strength and relatively low environmental impact. However, despite energy savings during precursor calcination, metakaolin-based systems may have higher overall implications due to high  $\text{Na}_2\text{SiO}_3$  content. FA offers modest emission reductions and remains a potential option when locally available. Hybrid mixtures combining different precursors may effectively compromise mechanical performance and environmental sustainability. The curing regime further affects GPC's sustainability profile. High-strength mixtures often require elevated-temperature curing to reach target mechanical properties, introducing additional environmental trade-offs compared to ambient PCC curing. Therefore, careful design of curing conditions is necessary to minimize the carbon footprint while maintaining structural performance.

Transportation also contributes noticeably to environmental impacts. While PCC typically relies on locally sourced materials, GPC components such as  $\text{Na}_2\text{SiO}_3$  and metakaolin are often regionally constrained, resulting in higher and more variable transport-related emissions. Utilizing locally available industrial by-products, such as construction and demolition waste, mine tailings, or fiber residues, can substantially reduce carbon emissions and logistical costs.

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