Geopolymer Concrete as a Revolutionizing Technology for Low-Carbon Construction: A Conceptual and Policy-Oriented Review

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Abstract. Construction industry is a global economic driver promoting globalization and at the same time, one of the high carbon emitting industries in the world. Ordinary Portland Cement (OPC),the main binder in concrete, contributes to 78 per cent of world anthropogenic CO_2 emissions because it is an energy-consuming clinker fabrication and a calcination of limestone. In the fast urbanizing economies such as India, whereby the infrastructure projects are increasing the pace of concrete demand, reducing the environmental footprint of construction is a pressing policy concern.The geopolymer concrete (GPC) is a revolutionary low-carbon concrete which replaces the cement content. Geopolymer concrete is made with alkali-activated aluminosilicate binders of industrial by-products such as fly ash, silica fume,ground granulated blast furnace slag (GGBS), red mud etc. This is an overall conceptual and policy-focused analysis that defines the challenge of a carbon-intensive construction and defines a review-based approach to sustainable alternatives and makes GPC a viable solution. Comprising quality life-cycle analysis (LCA) studies, durability research, and sustainability literature, it emphasizes the emission reduction, resource efficiency, and long-term performance by GPC.
In addition to the materials, the paper incorporates GPC into global (UN SDGs) and national (Smart Cities Mission of India) systems, dealing with governance, regulation, and implementation. GPC is technically feasible, environmentally superior to OPC concrete, and policy-relevant to low-carbon, circular, climate-resilient infrastructure in both developing and developed economies.
Keywords: Geopolymer concrete; Circular economy; Life-cycle assessment.

1. Introduction

The economic growth, infrastructure, and urbanization all over the world rely on the construction industry. Concrete, the most-represented vehicle of artificial material on the planet, is dominant because it is very versatile, strong, durable, and low-cost (Mehta and Monteiro, 2014; Scrivener et al., 2018; Habert et al., 2020). However Ordinary Portland Cement (OPC), which is its main binder causes extensive environmental damage. Manufacture of OPC, calcined limestone ($CaCO_3$) at high temperatures above 1400^0C in the course of burning fuels and decomposing minerals,which produces huge amount of CO_2. It contributes to 7-8 percent of the total anthropogenic emissions (Scrivener et al., 2018; Andrew, 2019; Le Quéré et al., 2018). Turner and Collins (2013) estimated that OPC concrete life-cycle emissions

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(365–428 kg CO_2-eq/m3) are a burden on country climate objectives when considering mega-sized construction projects.

The effects are felt in India as the country is the second-largest cement manufacturer in the world. Such programs as Smart Cities Mission, Bharatmala, Sagarmala, industrial corridors, and affordable housing, hype the demand, and with forecasts of new emissions spurts, there are no alternatives instead of find some solution regarding carbon di oxide emission (Government of India, 2023; World Cement,2025). Massive by-products of parallel industrial development are 340 million tonnes of fly ash (FY 2024-25), 11 million tonnes of GGBS, and millions of tonnes of red mud every year produced but the majority are in landfills leading to soil degradation, heavy metals leaching, contaminated groundwater, and loss of land (Ministry of Power, 2025).This linear take-make-dispose model uses up resources and discards chemically ideal precursors (Davidovits, 2015; Ellen MacArthur Foundation, 2015).

Geopolymer concrete (GPC) is made with the alkaline activator. Alkaline activation of aluminosilicate wastes such as fly ash, GGBS, and red mud, calcined clay based GPC,metakaolin and many other industry wastes eliminates clinker firing. This lead to reduce 20-80% of CO_2 emissions, provides higher durability (sulfate/chloride resistance) and circular valorization (Provis & bernal.,2014; Rashad, 2013; Turner and Collins, 2013; Zaland et al., 2025; Duxson et al., 2007; Fernández-Jiménez & Palomo, 2005). The transformation of wastes into high-value binders play a great role in the sustainable construction. GPC will fit construction in the global imperatives -Paris Agreement, UN SDGs 9/11/12/13 (resilient infrastructure, urbanization, resources, climate action) and India NDCs (45% reduction in emissions intensity by 2030) (UNEP, 2020; United Nations, 2015; Government of India, 2022). Although such pilots as Delhi Metro pavements exists, obstacles still remain in the field of scalability, BIS standardization, economics(MoEFCC, 2017; Mangla, 2021). These problem could be crossed by policy incentives, Research & Development, and green procurement, which would trigger low-carbon revolutions (Asian Development Bank, 2015).

Although experiments and research in this topic confirm the strength/durability of GPC (Provis and Bernal, 2014; Duxson et al., 2007), there is little evidence on integrative reviews that combine technical, sustainability, and policy thinking and analysis- especially in India (Turner and Collins, 2013; McLellan et al., 2011; Hardjito and Rangan,2005). This gap is filled in this paper through the holistic synthesis of peer-reviewed evidence, and GPC is presented as a systemic facilitator of a circuit of infrastructure (Davidovits, 2015; Habert et al., 2020).

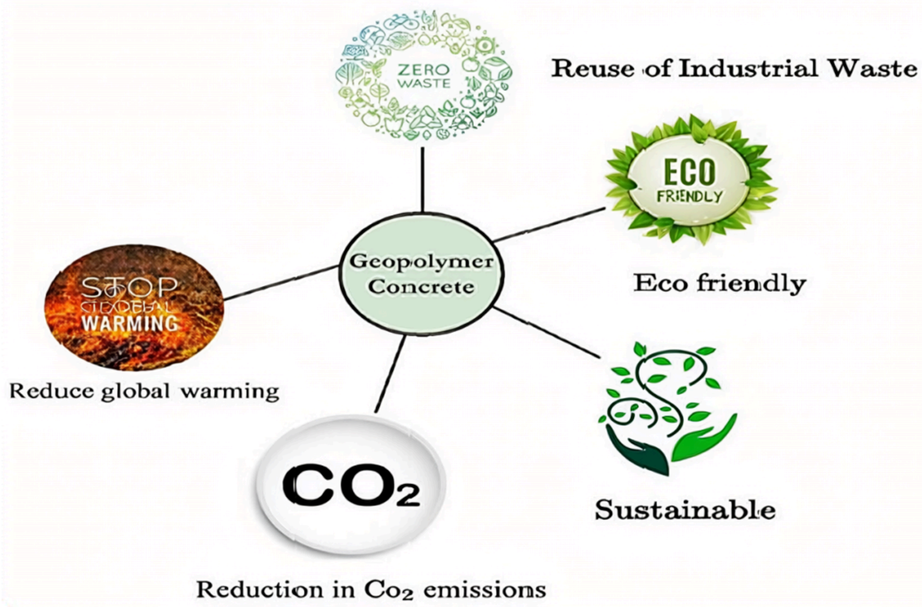

Fig 1. Advantages of GP-concrete usage for sustainable constructions (Source: Alawi et al., 2023)

This review aims to explain OPC's contribution of global CO_2 emissions (Fig 1), elucidate the chemistry of geopolymer concrete (GPC) and its potential for achieving the amount of emission reductions through waste utilization, synthesize durability performance including sulfate and acid resistance, align with Sustainable Development Goals 9, 11, 12, and 13 as well as India's Nationally Determined Contributions, and identify barriers such as standardization challenges alongside pathways including incentives and pilot program. Combining material science and policy perspectives, this review positions GPC as a transformative paradigm for waste-valorizing, low-carbon construction.

2. Research Methodology

The potential of geopolymer concrete (GPC) as a low-carbon substitute for regular Portland cement (OPC) is investigated in this study using a conceptual and policy-oriented literature survey. The review summarizes research on geopolymer materials, sustainability evaluation, and circular economy construction techniques from peer-reviewed journal articles, technical reports, and international policy documents.

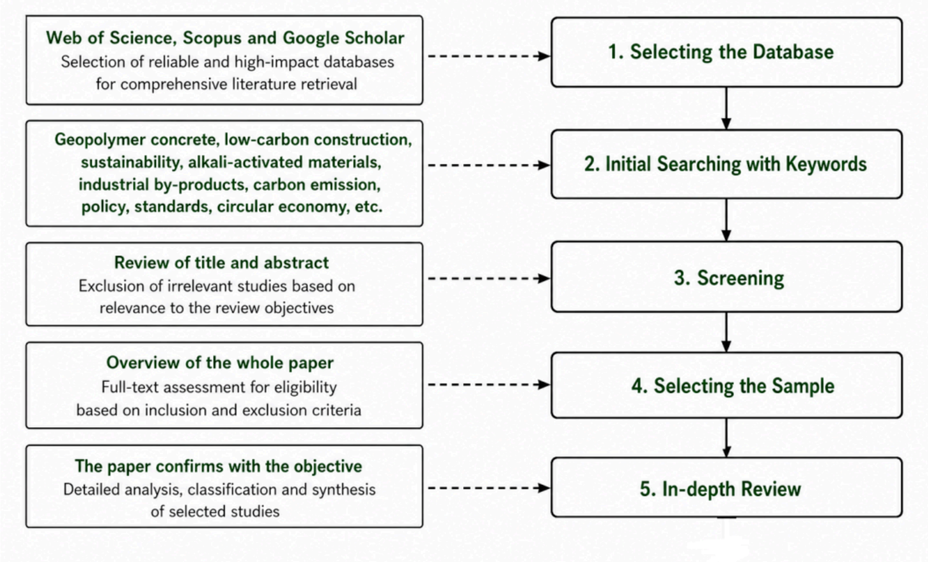

Fig. 2. The five-step workflow for reviewing the literature(Datta et al., 2024)

The main academic databases from which the literature was gathered were Scopus, Web of Science, Google Scholar, and Science Direct(Fig.2). The keywords used for the search geopolymer concrete; circular economy; life-cycle assessment; policy framework; climate-resilient infrastructure.In order to incorporate both contemporary developments in sustainability and life-cycle evaluation as well as fundamental research on geopolymer chemistry, publications from about 2000 to 2025 were taken into consideration. Three criteria were used in the inclusion of sources: Chemistry, mix design, durability, and structural performance are all relevant to geopolymer concrete technology, The Geopolymer concrete and traditional Portland cement concrete are compared in environmental and life-cycle assessment studies and Literature on policy and governance that discusses climate mitigation techniques, circular economy frameworks, and sustainable building. Any paper that does not study geopolymers, alkali-activated systems or any type of sustainable cementitious system was excluded. Papers studying Ordinary Portland cement only, without any comparison to low carbon cementitious systems were discarded. Further papers lacking detailed technical, environmental or policy-related information and any paper studying any non-construction application of geopolymers (catalyst, ceramics, waste immobilization etc.) were excluded. In order to avoid including double counts and not peer-reviewed studies (editorials, newsletters, opinions, patents, unpublished papers etc) and foreign language paper without dependable translation, papers published in these formats were not considered.

More than 60 peer reviewed publications were investigated and synthesized to understand key trends regarding emission reduction, durability performance, resource circularity, and policy pathway toward implementation. A comprehensive and integrative synthesis bridging sustainable policy landscape and materials science evidences is presented.

3. Chemistry Of Geopolymer Concrete (GPC)

Geopolymer concrete reinvents the construction using low-carbon through the replacement of hydration chemistry of Ordinary Portland Cement by using alkali activation of aluminosilicates to form a durable Si-O-Al network (Davidovits, 1991; Provis and van Deventer 2009). The process of such geopolymerization include dissolution-polymerization-gelation (*Fig.3*) removes the clinker calcification process, which lowers the emissions by 20-80% and gains the compressive strengths of up to 100 Mpa and better acid/ sulfate resistance (Duxson et al., 2007; Hardjito et al., 2004; Bakharev, 2005).

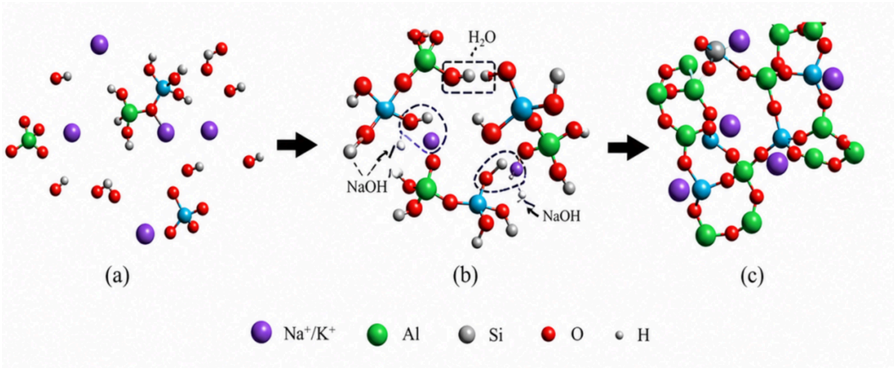

Fig.3 Schematic diagram for geopolymerization process: (a) reorganization of aluminosilicate, (b) gel formation from oligomers condensation, and (c) polymerization from Ref. [S. Zaland et al.,2025]

Dense microstructures can be used in ambient or heat-cured services, and even higher than OPC long-term service (Provis & Bernal, 2014; Fernandez-Jimenez et al., 2005). Life-cycle assessments assure the superiority of geopolymers where the decoupling of concrete with the OPC near 0.8 t CO_2/t clinker standard allows the creation of infrastructure with a net zero (Scrivener et al., 2018; McLellan et al., 2011; Turner and Collins, 2013).

3.1 Geopolymer Precursor

Geopolymer binders are pushed by aluminosilicate precursors that are predominantly composed of reactive SiO_2 /Al_2O_3 - Class F/C fly ash obtained by coal plants, ground granulated blast furnace slag obtained by steel industry, metakaolin obtained by calcined clay, and red mud obtained by alumina based industries(Davidovits, 2015; Provis and van Deventer, 2009). Fly ash contains glassy phases to be polymerized; GGBS allows ambient to cure by using hybrid N-A-S-H/C-S-H gels (Bernal et al., 2014; Puertas et al., 2000). Metakaolin produced by kaolinite clay, which is heaten up at very high temperature 600-800^{0}C under controlled condition to generate pozzolanic and reactive material.
Geopolymers occupy 70-100% by mass, diverting landfills and reducing virgin limestone/clay mining compared to OPC (Ellen MacArthur Foundation, 2015). LCAs exhibit 40-60% embodied energy reduction and 80 percent landfill decrease (Habert et al., 2020; McLellan et al., 2011).The addition of red mud makes it alkaline (pH 10-13) and uses bauxite waste to the best of its abilities (He et al., 2011).

3.2 Alkaline Activators and optimisation Pathways

Alkaline activators drives geopolymerization by dissolving SiO_2 and Al_2O_3 from precursors like fly ash or GGBS, enabling polycondensation into a robust Si-O-Al network (Davidovits, 2015). Common formulations include sodium hydroxide (NaOH) at 8-14 M concentrations, potassium hydroxide (KOH), sodium silicate (Na_2SiO_3, modulus 2-3.5), and potassium silicate (K_2SiO_3), with silicate/hydroxide ratios of 1.5-2.5 optimizing kinetics and strength (Davidovits, 2015; Hardjito et al., 2004). Higher molarity accelerates dissolution but risks efflorescence; blended activators balance reactivity and workability (Zhang et al., 2019).They emit up to 20-40% of geopolymer emissions ,which makes net 60-80% CO_2 savings over OPC (0.3-0.5 kg CO_2-eq/kg for geopolymer binder vs. 0.9 kg CO_2-eq/kg for OPC binder) (Turner and Collins, 2013; Habert et al., 2020; Salas et al., 2018).
Alkaline activators are harmful to handle.For safety concern(corrosivity and handling) ,one-part geopolymer system is adopted in which add water directly to the binding material powders with low alkalinity (Na_2CO_3, sulfoaluminates). This construction way may become cost-effective construction (using precursors comprising 30–50% of the binder mass), easy handling without corrosive liquids, and compressive strengths reaching 70–100% of OPC performance levels (Luukkonen et al., 2018).R&D, standardization, and OPC-geopolymer hybrids need policy incentives to be adapted at scale in circular construction (Provis, 2018).

Geopolymer concrete is affected significantly by the production of alkaline activators. One or both of sodium silicate and sodium hydroxide are usually the main contributors to CO_2 in construction, and non-CO2 emissions (in life-cycle assessments of geopolymer concrete), and at higher levels, can reverse the advantage of reducing clinker (Farooq et al., 2021; Meskhi et al., 2023; Sharma et al., 2024). In the case of geopolymer concrete, the transportation of the precursors and activators contributes to the overall emissions and reduced the benefits, hence the source and selection of alkaline activator needs to be considered (Nawaz et al., 2020; Nodehi and Taghvaee, 2021). In addition, the benefits of geopolymer concrete are influenced by the carbon content of the electricity, with low carbon electricity enhancing the benefits and high carbon electricity reducing the benefits (Shehata et al., 2022; Ricciotti et al., 2025).

4. Circular Economy Framework and Sustainability.

4.1 Geopolymer Concrete within a Circular Economy Model.

The principles of circular economy are resource efficiency, absence of waste, and closed-loop cycles, which are the principles geopolymer concrete (GPC) satisfies by transforming industrial by-products, such as fly ash and ground granulated blast-furnace slag (GGBS), into high-performance binders, reducing virgin material consumption and landfill (Ellen MacArthur Foundation, 2015; Provis, 2018).
The LCA confirm that GPC is better than ordinary Portland cement (OPC) concrete, consuming less energy over its entire life cycle, less primary resources, and creating industrial symbiosis, i.e., the waste of power/steel industries are the construction fuel (Turner and Collins, 2013; Habert et al., 2020). Construction demolition waste (CDW) like recycle aggregates enhance cyclic activity not only in terms of properties ,durability and mechanical performance of natural mixes but also in terms of extraction ,reduction and diversion of up to 80 percent more waste to the landfill (Imtiaz et al., 2021; Zhang et al., 2023). Minor changes in strength (5-15% using low-quality aggregates) are advantageous in the case of infrastructure/non-structural applications, as denser geopolymer paste improves recycled aggregate bonding (Davidovits, 2015).

4.2 Efficient Resource use and Reduction in embodied carbon

Embodied carbon in the form of trapped greenhouse gas emissions of production, transport, and construction must be mitigated with alternatives such as GPC that avoids the OPC expensive clinker bottle-neck.
LCAs measure 30-80% carbon saved on embodied reduction compared to OPC concrete, which is a result of precursor selection, low-emission activators, and ambient curing e.g., fly ash-GGBS blends have 0.2-0.4 t CO 2-eq/m3- versus OPC 0.4-0.5 t (Turner and Collins, 2013; Ansari et al., 2023; Martínez & Miller, 2024,Salas et al., 2018; Habert et al., 2020). Such gains are compounded with recycled aggregates (further 20-40% reductions) and waste precursors, reducing the potential of global warming and enhancing efficiency of resources in high-waste situations such as a 340 Mt /year fly ash stream in India (Ministry of Power, 2025). These metrics need to be used in policy design through public projects requirements, and they must align GPC with SDGs 12 (responsible consumption) and circular infrastructure objectives (United Nations, 2015).

5. Comparative Life-Cycle Performance

LCAs measure the total environmental footprint of construction materials on a cradle-to-grave basis, and geopolymer concrete (GPC) is superior to ordinary Portland cement (OPC) in the measure of both global warming potential (GWP) and resource

consumption (Salas et al., 2018; Turner and Collins, 2013).The nine studies on meta-analyses of LCAs show that fly ash-GGBS GPC achieves 53-54% GWP reductions ,CDW-based mixes 21% , and metakaolin optimisation results in an additional 16% cuts(Imtiaz et al., 2021; Bamshad & Ramezanianpour, 2024) . Activators enhance trade-offs in ecotoxicity/eutrophication (10-30% improved), highlighting the aspect that C2C needs must consider service life (Imtiaz et al., 2021; Bamshad & Ramezanianpour, 2024).
Geopolymer concrete (GPC) has been proven to be superior to ordinary Portland cement (OPC) concrete, with global warming potential (GWP) reductions of 21-54% with a variety of precursors and in diverse locations (Salas et al., 2018; Imtiaz et al., 2021; Turner and Collins, 2013).

5.1 Environmental Trade-offs

Alkaline activators (sodium hydroxide, sodium silicate) enhance marine eco-toxicity and human toxicity and eutrophication potentials, which require equitable multi-impact evaluation (Imtiaz et al., 2021). Net superiority is obtained when the cradle-to-cradle analysis is done considering the long service life and recyclability of GPC (Bamshad & Ramezanianpour,2024).

5.2 Methodological Advances

Predictive accuracy and supply chain integration are improved when AI-optimized LCA frameworks are used (Ramesh et al., 2025). Such advancements confirm the feasibility of GPC as a scalable low-carbon alternative, provided that standardized LCA protocols are used. Life cycle assessment data for geopolymer concrete compared to ordinary Portland cement(table 1). Geopolymer concrete typically shows a reduction in global warming potential and in the total cumulative energy demand, whereas eco toxicity may be enhanced.

Table 1: Comparison between GPC and OPC LCA Performance

Impact Category	**OPC (kg CO_2-eq/m³)**	**GPC (kg CO_2-eq/m³)**	**Reduction (%)**	**Key References**
GWP	350-450	150-280	30-60	Turner & Collins (2013); Salas et al. (2018)
CED (GJ/m³)	2.0-2.8	1.2-1.8	30-40	Habert et al. (2020); McLellan et al. (2011)
Ecotoxicity	Baseline	+10-30%	Trade-off	Imtiaz et al. (2021)

Table 2 compare mechanical and durability properties of Ordinary Portland Cement (OPC) vs Geopolymer Concrete (GPC) which discusses properties like compressive strength, embodied carbon, sulphate resistance, and fire resistance, highlighting performances benefits and sources.

Table 2: GPC Mechanical/Durability Benefits.

Property	OPC Range	GPC Range	Advantage (%)	References
Compressive Strength (MPa)	20-40	40-65+	Increased by 50-80	Hardjito & Rangan (2005); Provis & Bernal (2014)
Embodied Carbon (kg/m³)	350-450	150-280	Reduced by 30-60	Andrew (2019); Ansari et al. (2023)
Sulfate Resistance	Poor	Excellent	2-5x	Bakharev (2005)
Fire Resistance (°C)	Spalling @800	Stable @1200	2-3x	Duxson et al. (2007)

When using local sourcing (i.e., fly ash of India), 40-60 percent net savings are maintained despite the activators/ transport (Habert et al., 2011; Ramesh et al., 2025).

5.3 Relevance of LCA Policy

LCA supports performance-based policies: the carbon 40-60% GWP reductions of GPC justify carbon targets (>20% savings) during tender, green procurement, and new codes (RILEM TC 247-DMG, 2019; Meskhi et al., 2023). This replaces OPC requirements with lifecycle measures, which are in line with SDGs 9/11/12/13 and the NDCs in India (United Nations, 2015). Table 3 shows the recommended policy with global alignment.

Table 3: GPC Transformation Matrix of Policy.

Dimension	GPC Advantage	Policy Instrument	Global Alignment
Environmental	Reduced 40-60% GWP	LCA mandates in public tenders	Paris NDCs, EU Taxonomy
Circular	80% waste utilization	Fly ash mandates expanded	SDG 12
Durability	20-50% life extension	Lifecycle costing	SDG 9/13
Economic	Reduced 10-20% lifecycle cost	Carbon pricing/subsidies	SDG 11

In short, When geopolymer concrete replaces OPC-based systems, the majority of studies consistently report significant reductions in embodied carbon; however, the extent of these reductions varies based on precursor availability, activator composition, curing techniques, and industrial by-product transportation distance. This difference emphasizes how crucial regional supply chains and material availability are to figuring out how well geopolymer systems actually function in terms of the environment. Therefore, localized industrial symbiosis—the integration of waste streams from power plants, steel companies, and alumina refineries into construction supply chains should be taken into account in regulatory frameworks that encourage the deployment of geopolymers.

6. Durability, Service Life and Climate Resilience.

6.1 Durability Mechanisms

The compact Si-O-Al microstructure of geopolymer concrete (GPC) gives it a better durability compared to ordinary Portland cement (OPC), which reduces permeability and free calcium, which is one of the major deterioration agents (Bakharev, 2005). This increases service life and enhances the low-carbon benefit of GPC due to lower cost of maintenance (Turner & Collins, 2013).

6.2 Chemical and Environmental Resistance

Durability, mechanical, environmental and sustainability checks are given to conclude the chemical and environmental resistance. Table 4 shows performance comparative assessment of GPC vs OPC including CO2 emissions, global warming potential in lifecycle, sulphate resistance, chloride resistance, carbonation, freeze-thaw, acid resistance, fire resistance, permeability, alkali-silica reaction, use of recycled aggregate, strength development, embodied energy, costs-trade offs, circular economy potential, and the potential of artificial intelligence-based assessment, along with literature data on comparative performance benefits.

Table 4: GPC vs. OPC Durability Performance

Factor	OPC Performance	GPC Performance	Advantage	References
GlobalCO_2 Emissions (Binder Level)	~0.85–0.95t CO_2/t clinker	30–80%lower depending on mix	Significant embodied carbon reduction	Andrew (2019); Turner & Collins (2013); Habert et al. (2020); Martínez & Miller (2024)
Life Cycle GlobalWarming Potential (Concrete Level)	Higher cradle-to-grave GWP	20–60%lower GWP	Reduced life cycle impact	Salas et al. (2018); Bamshad & Ramezanianpour (2024); Imtiaz et al. (2021)
Sulfate Resistance	Susceptible to expansion & cracking	Improved sulfate resistance	Enhanced durability in aggressive soils	Winnefeld et al. (2020); Wong (2022); Zaland et al. (2025)
Chloride Penetration/ RCPT	Moderate to high permeability	Lower charge passed, denser matrix	Improved corrosion resistance	Gopalakrishna & Dinakar (2024); Zhang (2023); Shumuye et al. (2022)
Carbonation Resistance	Progressive carbonation	Comparable or mix-dependent performance	Optimizable with slag/metakaolin	Guo et al. (2025); Zhang (2023); Zaland et al. (2025)
Freeze–Thaw Resistance	Performance reduces under cyclic exposure	Generally improved resistance	Better cyclic durability	Winnefeld et al. (2020); Yang et al. (2023); Wong (2022)
Acid Resistance	Calcium Dissolution (C–S–H degradation)	Reduced mass loss in acidic media	Improved acid stability	Bakharev (2005); Rashad et al. (2025); Zhang (2023)
High Temperature / Fire Resistance	Strength loss & spalling At elevated temperatures	Better structural stability at high temperature	Superior thermal performance	Duxson et al. (2007); Zaland et al. (2025); Wong (2022)
Permeability & Sorptivity	Higher capillary suction	Denser microstructure, lower permeability	Improved durability index	Fernández-Jiménez & Palomo (2005); Chand (2021); Wong (2022)
Alkali–Silica Reaction (ASR)	Potential ASR expansion	Reduced reactive silica dissolution	Lower ASR risk	Winnefeld et al. (2020); Zaland et al. (2025)
Recycled Aggregate Compatibility	Strength reduction with RCA	Improved ITZ bonding in geopolymer matrix	Better RCA integration	Pawluczuk et al. (2021); Nikmehr & Eryılmaz& Polat (2024)
Mechanical Strength	Hydration-based	Comparable or higher	High-strength potential	Hadi et al. (2017); Karthik et al. (2017)

Development	strength gain	compressive strength achievable		
Long-Term Strength Evolution	Plateau after 90 days	Continued polymerization-based strength gain	Improved long-term performance	Provis & Bernal (2014); Samantasinghar & Singh (2019); Moodi et al. (2025)
Embodied Energy	High due to clinker production	Reduced energy demand	Energy-efficient binder system	Habert et al. (2020); Scrivener et al. (2018); Martínez & Miller (2024)
Cost&Carbon Trade-Offs	Established supply chain	Slightly higher activator cost but lower lifecycle cost	Competitive in lifecycle terms	McLellan et al. (2011); Martínez & Miller (2024); Ansari et al. (2023)
Circular Economy Potential	Limited industrial waste incorporation	High utilization of fly ash, slag, recycled aggregates	Strong Circularity contribution	Bamshad & Ramezanianpour (2024); Mir et al. (2022); Zhang et al. (2023)
AI-Optimized Sustainability Assessment	Conventional LCA	AI-based predictive LCA emerging	Improved decision-making	Ramesh et al. (2025); Siddiq et al. (2025)

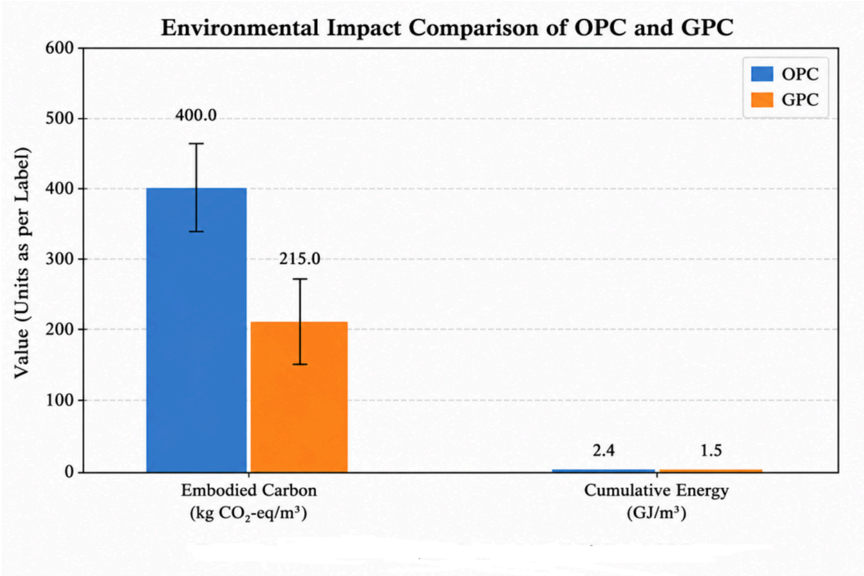

Fig.5. Comparative analysis of environmental impact parameter OPC vs. GPC{Data Sources and Citation: Scrivener et al.(2018), Turner & Collins (2013), Provis & van Deventer (2009), Habert et al. (2020),McLellan et al. (2011), Zhang et al. (2023), Hardjito and Rangan, (2005)}

Fig 6 is the Radar chart on the relative performance of plain ordinary portland cement (OPC) concrete and geopolymer concrete (GPC) in compressive strength, flexural strength, density, durability, acid resistance, energy requirement and embodied carbon (higher values on mechanical and durable aspects as well as the environmental aspects indicates good performance).

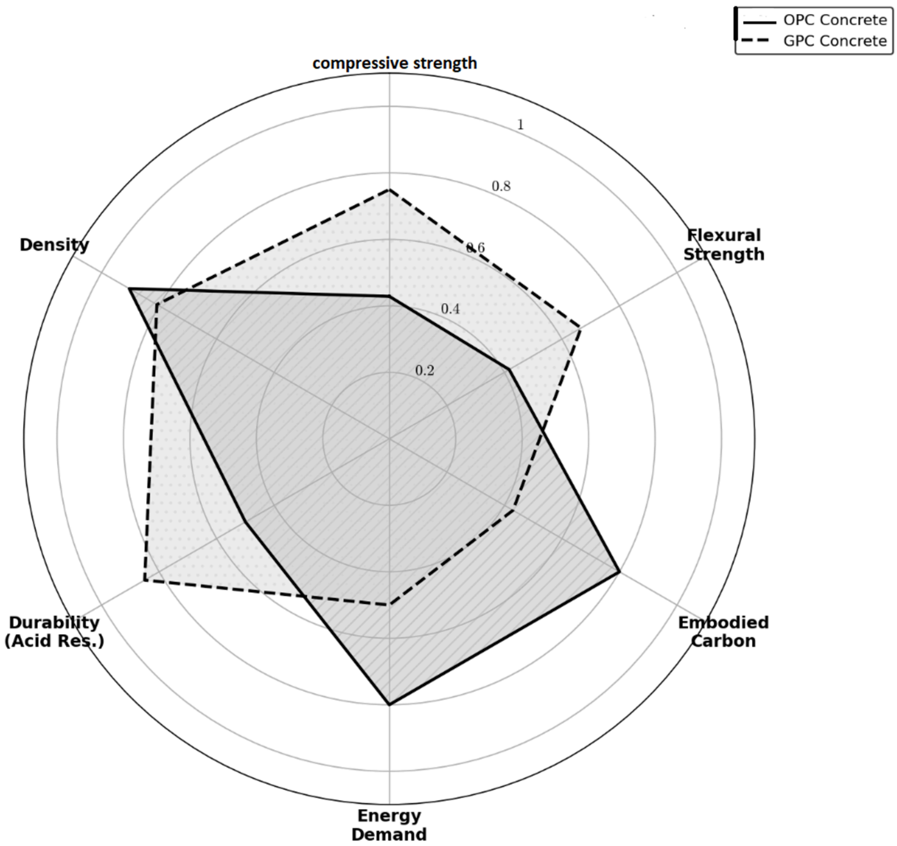

Fig. 6. *Comparison in visual form OPC vs. GPC{Data Sources and Citation: Scrivener et al.(2018), Turner & Collins (2013), Provis & van Deventer (2009), Habert et al. (2020),McLellan et al. (2011), Zhang et al. (2023)}*

Geopolymer concrete has been proven to be more durable in a variety of factors than OPC (supported by existing research). GPC contains low levels of $Ca(OH)_2$, which reduces the chances of corrosion during carbonation, which is suitable to coastal/marine service.

6.3 Life-Cycle Benefits

Geopolymer concrete (GPC) has 20-50 percent more service life than the ordinary Portland cement (OPC), which triples its 40-60 percent carbon savings embodied in lifecycle performance (Provis & van Deventer, 2009). Increased resistance to sulfate, acid, and thermal attacks, means that maintenance is improved by 30-40 per cent. whole-life costs go down (Davidovits, 2015). Lifecycle assessment indicates that

GPC structures have a service life of 100 or more years with 50 to 70 percent less CO_2 equivalent emissions including reduction of repair (Turner and Collins, 2013).
The low-alkali formulations of GPC reduce leaching during the course of many decades and maintain the integrity of the ecosystem compared to the portlandite dissolution in OPC (Bakharev, 2005). Together with recycled precursors, it reduces the consumption of virgin materials by 80 percent, leading to greater benefits of a circular economy (Duxson et al., 2007).
Net present value models indicate that GPC would achieve up to 25-35% savings on lifecycle costs in harsh conditions that are caused by limited number of interventions (McLellan et al., 2011). Service life modelling is estimated to withstand 1.5- 2x longer spans when subjected to chloride thus postponing replacement by 20-30 years.

Table 5 Comparing OPC and GPC performance across key parameters. It shows that OPC has higher embodied carbon (400–600 kg CO_2/m^3) compared to GPC, which achieves a 40–60% reduction due to the absence of clinker calcination. Service life improves from 50–70 years for OPC to 20–50% longer in GPC, attributed to the formation of dense N-A-S-H gel structures. Maintenance cycles in OPC occur every 10–15 years, while GPC requires roughly half the frequency due to better acid and sulfate resistance. Over a 100-year period, total CO_2 emissions are 800–1200 kg/m³ for OPC versus 400–700 kg/m³ for GPC, reflecting improved durability and lower lifecycle environmental impact.

Table 5: Performance in various parameters

Parameter	OPC	GPC Improvement	Main Reason (References)
Embodied Carbon	400-600 kg CO_2/m^3	40-60% reduction	No clinker calcination (Provis & van Deventer, 2009)
Service Life	50-70 years	+20-50% extension	Dense N-A-S-H gels (Yang et al., 2019)
Maintenance Cycles	Every10-15 years	Halved frequency	Acid/sulfate resistance Bakharev (2005); Rashad et al. (2025); Zhang (2023)
Total CO_2 (100 yr)	800-1200 kg/m³	400-700 kg/m³	Durability compounding (Turner & Collins, 2013)

The advantages put GPC in the best position to be sustainable infrastructure, and tested models have confirmed net positive across metrics (Habert et al., 2020).

7. International and National policy alignment

Geopolymer concrete is align with the United Nations Sustainable Development Goals (SDGs), which aim to promote SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) with the low-carbon material utilization and valorization of waste (United Nations, 2015).

The life-cycle assessment validates significant CO_2 emissions savings and industrial symbiosis through by-product recycling, which makes geopolymer a scalable solution to the principles of circular economy (Provis & bernal.,2014; Habert et al., 2020).
Geopolymer concrete is a solution in India to the Smart Cities Mission of resource-efficient, climate-resilient infrastructure and Paris Agreement requirements to cut sectoral emissions (Meskhi et al., 2023). Another advantage is the utilization of construction and industrial waste (as geopolymer concrete can include, coal fly ash, ground granulated blast furnace slag, rice husk ash, demolition fines, and bottom ash from municipal solid waste incineration), which reduces landfill waste and improves the circular economy (Nodehi and Taghvaee, 2021; Nawaz et al., 2020; Poranek et al., 2022; Kumar et al., 2025). This also reduces the need for primary construction materials, and helps many of the Sustainable Development Goals, especially on sustainable cities and communities and climate action (Shehata et al., 2022; Kumar et al., 2025; Ikotun et al., 2024).The adoption rate is however poor because OPC dominated standards are used which do not allow other binders, and which even promise pilots in roads and housing. It is crucial to change the policies to close this gap and achieve the national sustainability objectives (Khasawneh, 2025).
GPC promotes SDGs 9/11/12/13 through 40/80% carbon di oxide cuts and 80% waste valorization, which sustains the Smart Cities Mission and NDCs in India (United Nations, 2015; Meskhi et al., 2023).

8. Barriers, Opportunities and Implementation Pathways

Geopolymer concrete (GPC) is much less carbon-intensive compared to Ordinary Portland Cement (OPC). However, many barriers exist in the technical, regulatory, and institutional contexts that make its implementation very difficult. Some of the challenges in the technical domain include the use of caustic alkaline activators, the inconsistent quality of industrial aluminosilicate, and the use of thermal curing in the industry (Provis & van Deventer, 2009; Hardjito and Rangan, 2005). As for the regulatory phase, building codes for GPC are yet to be written and the existing BIS codes are OPC-prescriptive and not performance-based (Meskhi et al, 2023; Khasawneh, 2025). From an institutional point of view, barriers include GPC being unfamiliar to most engineers, the uncertainty of long-term performance and the focus of procurement on prescriptive OPC specifications rather than performance (Luhar and Luhar, 2022).
Some barriers in this phase can be addressed with the following strategic recommendations: move from prescriptive to performance-based codes (RILEM TC 247-DMG, 2019; Provis, 2018), make procurement contracts mandatory with life cycle assessments (LCA) showing >20% savings in global warming potential (GWP) (Meskhi et al., 2023), create 20 year monitoring LT pilot projects (Delhi Metro model), invent one-part dry mix geopolymers to make GPC easier to use (Zhang et al., 2019), and add GPC to sustainability certification(LEED, BREEAM) with carbon pricing and GPC Research and Development from academia, industry and government (Meskhi et al., 2023; Salas et al., 2018).
There are many ways to build capacity in the industry and allow for knowledge

transfer and acceptance. These include workshops, changes to course materials, online repositories for mix-designs, and demonstration projects of geopolymer pavements and fire-resistant panels (Luhar and Luhar, 2022; Provis, 2018). The use of hybrid activators is one of the emerging opportunities.

9. Conclusion And Future Scope

This review summarizes the potential of Geopolymer Concrete (GPC) in different direction and find out GPC helps in reducing the global warming effects by 40-60% compared to traditional methods of concrete production. This is due to the low carbon emissions of GPC and the incorporation of industrial by-products. GPC aligns with the principles of a circular economy, as it uses 80% of by-product waste and reduces landfill demand. For aggressive environments (acid and sulfate exposure), GPC extends the service life of structures by 20-50%. This decreases overall maintenance and lifecycle costs, which also reduces GPC costs by 10-20% compared to traditional concrete. The "Geopolymer Paradox" is the contradiction of activator products (sodium silicate and sodium hydroxide) causing clinker production as a result of GPC; however, low-activated, waste-derived geopolymer systems and regional resources, decarbonization lifecycle assessments can counter this paradox. It is likely that an increase in GPC use will greatly aid in the reduction of global cement emissions. As a bonus, the use of industrial by-products aligns with the (SDGs 9, 11, 12, and 13) and promotes sustainable, resilient infrastructure and responsible consumption by supporting climate action.

Beginning in 2026, Geopolymer concrete should be the focus of new policies. GPC should be incorporated into public contracts by mandating bids to contain concrete with a 20% reduction or more in GWP. Proposed contracts should contain subsidized pilot programs, using one-part GPC to scale production. Performance-based methodologies for GPC should be introduced into the Indian Standards (BIS) Code. Demonstrating the advantages of GPC should stimulate the low-carbon policies in the building and construction sector. The following policies should be implemented to achieve the goals of the BIS to develop geopolymers and alternate binders as the standard for public infrastructure by 2030. The construction industry should be focused on performance-based policies, carbon costs, and sustainability certifications (LEED, BREEAM) to achieve net-zero policies. In conclusion, geopolymer concrete is a realistic way of implementing low-carbon, long-lasting, and circular infrastructure systems, and should be viewed more than a minor enhancement to the building materials landscape. Further research can be carried out using different types of activator and blends to optimize its mix design and cost. Material selection should be based on sustainability criteria, waste utilization potential, and environmental considerations, aiming to enhance resource efficiency, minimize environmental impacts, and promote the development of low-carbon construction materials.

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