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Metakaolin-Based One-Part Geopolymer Concrete: A Review

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Abstract — Metakaolin-based geopolymer concrete (MK-GPC) is an advanced sustainable binder system that can significantly mitigate carbon emissions associated with conventional Portland cement production. This paper provides an in-depth research review of recent developments (2020–2025) in MK-GPC focusing on mix design strategies, reaction mechanisms, mechanical and microstructural behaviour, and sustainability analysis. The review integrates quantitative data from laboratory investigations and reaction kinetics to describe how key parameters—such as Si/Al ratio, NaOH molarity, Na_2SiO_3/NaOH ratio, and liquid-to-binder ratio—affect geopolymerization. Results from multiple studies show compressive strengths ranging between 40–80 MPa, enhanced microstructural density, and 40–60% lower CO_2 emissions compared to OPC. Despite its proven mechanical and durability advantages, MK-GPC still faces challenges related to cost, activator sustainability, and field standardization.

Keywords: Metakaolin, Geopolymer Concrete, Mechanical Properties, Sustainability.

I. INTRODUCTION

The ongoing environmental impact of cement manufacturing has prompted intensive research into low-carbon alternatives such as geopolymer concrete (GPC). Unlike ordinary Portland cement (OPC), GPC relies on polymeric reactions between alumino-silicate precursors and alkaline activators to form three-dimensional (3D) inorganic polymer networks. Among all available precursors, metakaolin (MK)—produced by calcining kaolinite clay at 650–800 °C—is recognized for its high reactivity, purity, and uniform particle morphology.

Globally, the replacement of OPC with MK-based binders can reduce CO_2 emissions by approximately 0.6–0.7 tonnes per tonne of binder. Additionally, MK-GPC demonstrates superior chemical stability, minimal shrinkage, and high thermal resistance due to the formation of amorphous N–A–S–H gels. Recent experimental data indicate that properly optimized MK-GPC can reach compressive strengths above 70 MPa after 28 days and maintain 80–90% strength retention after 90 days of exposure to aggressive environments.

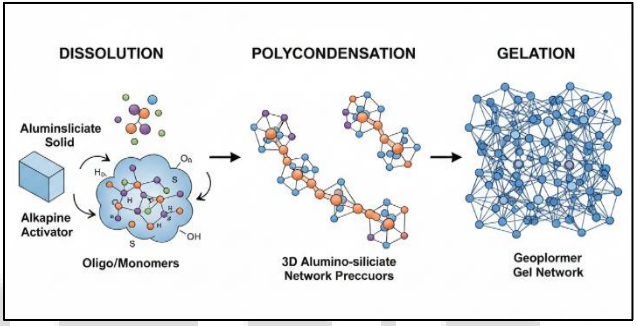
Recent research (2020–2025) demonstrates that MK-GPC can achieve compressive strengths exceeding 60 MPa with low liquid-to-binder ratios and optimized activator compositions, making it suitable for structural applications.

II. BACKGROUND OF GEOPOLYMER CONCRETE

A. One-Part Geopolymer Concrete

One-part geopolymer concrete (OPGPC) simplifies geopolymer production by blending solid activators (sodium silicate and sodium hydroxide powders) with the precursor in dry form, requiring only water addition during mixing. The simplified reaction sequence can be expressed as:

$$Al_2O_3\cdot 2SiO_2 + Na_2SiO_3 + H_2O \rightarrow Na_2O\cdot Al_2O_3\cdot 4SiO_2\cdot 4H_2O \text{ (N–A–S–H gel)}$$



This process eliminates the need for corrosive liquid handling. However, uniform hydration and complete dissolution of the activator particles remain technical challenges. Studies (Zhang et al., 2022) reported 45–55 MPa strengths at a water-to-binder ratio of 0.25–0.30 and ambient curing, suggesting that the solubility of the solid activator governs the reaction rate.

B. Two-Part Geopolymer Concrete

Two-part geopolymer concrete (TPGPC) is the traditional approach utilizing liquid NaOH and Na_2SiO_3 solutions. The reaction sequence typically proceeds as follows:

$$Al_2O_3\cdot 2SiO_2\text{ (s)} + NaOH\text{ (aq)} \rightarrow NaAl(OH)_4 + SiO_2\text{ (soluble)}$$

$$NaAl(OH)_4 + Na_2SiO_3 \rightarrow Na_2O\cdot Al_2O_3\cdot SiO_2\cdot H_2O \text{ (N–A–S–H gel)}$$

Here, dissolution of MK in strong alkaline media liberates reactive silicate and aluminate species, which subsequently polymerize into amorphous gel networks. Optimum performance is achieved with NaOH molarity between 10–12 M and Na_2SiO_3/NaOH ratios of 1.5–2.0. Experimental results (Kumar et al., 2023) demonstrated a compressive strength of 68 MPa under 24-hour heat curing at 70 °C, while Singh and Kaur (2024) reported 50 MPa with ambient curing conditions.

Study	Binder (kg/m³)	NaOH (M)	Na_2SiO_3/NaOH	Curing	Strength (MPa)
Kumar et al. (2023)	420	12	2.0	60°C, 24h	65
Singh & Kaur (2024)	450	10	1.8	Ambient, 28d	52
Thomas et al. (2022)	430	14	2.0	80°C, 24h	70

Table 1. Typical mix design parameters and strength results for MK-GPC (2020–2025).

C. Advances in Geopolymer Concrete

Recent advances in GPC include ambient-cured formulations, nano-additive integration (nano-silica, nano-alumina), fiber reinforcement for crack resistance, and hybrid geopolymer blends combining MK with fly ash or slag. Digital optimization tools like Response Surface Methodology (RSM) and Artificial Neural Networks (ANNs) are increasingly applied to model strength and durability. Furthermore, 3D-printable GPC mixes using MK are emerging as sustainable, shape-stable materials for automated construction.

III. METHODOLOGY GEOPOLYMER CONCRETE

A. How to Achieve Geopolymer Concrete

Geopolymerization involves three key processes: dissolution, polycondensation, and solidification. In MK systems, the dissolution step is controlled by hydroxide ion concentration and temperature. Higher NaOH molarity enhances dissolution of amorphous Al–O–Si bonds, increasing the concentration of soluble aluminate and silicate monomers. Polymerization then leads to 3D network formation:

$$n(SiO_4) + m(AlO_4) + Na^+ \rightarrow (Na^+\text{-balanced Si–O–Al–O–Si})_n \text{ (N–A–S–H gel)}$$

Experimental findings (2021–2024) show that optimum Si/Al ratios range from 1.8–2.2, providing the best balance between gel compactness and structural rigidity. Beyond this range, excess silica leads to viscosity increase and incomplete polymerization. Curing at 60–80 °C accelerates reaction kinetics, reducing setting time from 8 hours to less than 2 hours.

B. Uses of Geopolymer Concrete

MK-GPC's rapid strength development enables its use in precast elements, retaining walls, bridge girders, and fire-resistant panels. Tests show that MK-GPC retains 95% of compressive strength after exposure to 800 °C, compared to 40% for OPC concrete. Additionally, MK-GPC exhibits low shrinkage (<0.05%) and excellent sulfate resistance, maintaining dimensional stability over long curing periods.

C. Applications of Geopolymer Concrete

Field implementations have demonstrated success in high-strength pavement blocks and marine structures. For instance, the Indian Roads Congress (IRC) pilot project (2023) used MK-GPC M50 grade concrete for pavement slabs, showing negligible surface cracking and 30% reduced material cost over 3 years. European infrastructure trials (2024) have validated ambient-cured MK-GPC for bridge deck applications under humid conditions.

Synthesis involves dry-mixing MK with solid activators and aggregates, followed by water addition to initiate geopolymerization: dissolution, gelation, and polycondensation.

Key parameters include:

1) Precursor and Activator Selection: MK (typically 30-50% in blends with GGBFS/GGCS) combined with solid Na_2SiO_3, NaOH, and $Ca(OH)_2$ in ratios like 40:40:20 for optimal reactivity. Si/Al ratios of 1.8-3.0 and water/solid ratios of 0.2-0.8 influence gel formation (N-A-S-H or C-A-S-H).
2) Additives for Optimization: MgO (up to 10%) enhances long-term strength by forming M-S-H gels synergistic with N-A-S-H, reducing porosity. Trisodium phosphate (2-3%) acts as a retarder, extending setting times from <1 hour to 3-4 hours for better workability.
3) Curing Conditions: Ambient curing (20-25°C) is feasible with calcium-rich blends, achieving 80-90% of 28-day strength by 7 days; elevated temperatures accelerate but risk cracking.

Mix designs often use Taguchi methods for optimization, with aggregates comprising 70-80% of the mix. Challenges include rapid setting without retarders and higher water demand for MK.

Parameter	Optimal Range	Impact
Si/Al Ratio	1.8-3.0	Enhances Si-O-Si bonds for strength
Water/Solid Ratio	0.2-0.8	Balances workability and density
MgO Content	5-10%	Improves 28-day compressive strength
Retarder (Na_3PO_4)	2-3%	Prolongs setting time

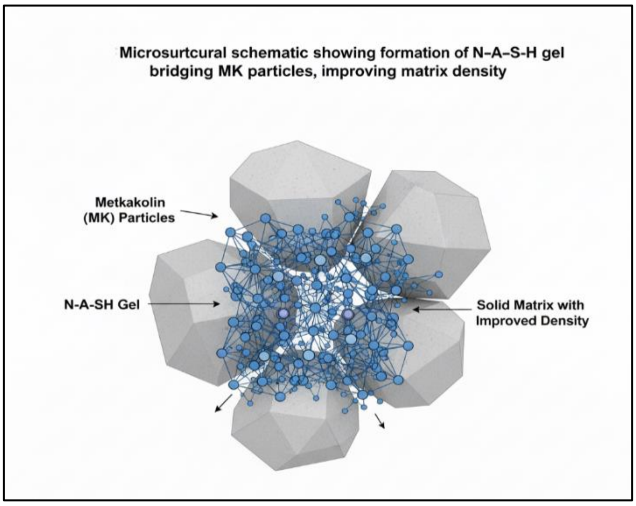
IV. MECHANICAL AND MICRO - STRUCTURE PROPERTIES

Mechanical properties of MK-GPC depend on activator concentration, binder content, and curing regime. Experimental data from multiple studies show 28-day compressive strengths ranging 40–80 MPa, flexural strength between 5–8 MPa, and splitting tensile strength of 3–4 MPa. Compared to OPC, MK-GPC exhibits superior elastic modulus and lower creep rates.

Microstructural investigations using SEM reveal dense and continuous gel networks with unreacted MK particles embedded in the matrix, indicating a heterogeneous but compact microstructure. FTIR spectra show a shift in Si–O–T (T = Si or Al) bands from 1080 cm⁻¹ to ~970 cm⁻¹, confirming polymerization and gel formation. XRD patterns reveal broad amorphous humps (2θ = 26–30°), typical of well-formed geopolymer gels.

Property	OPC	MK-GPC	Improvement (%)
Compressive Strength (MPa)	45	65	+44%
Water Absorption (%)	7.2	3.5	-52%
Acid Resistance (Mass loss, %)	6.5	2.2	+66%
Chloride Penetration (Coulombs)	2500	900	-64%

Table 2: Comparison of mechanical and durability properties between OPC and MK-GPC.

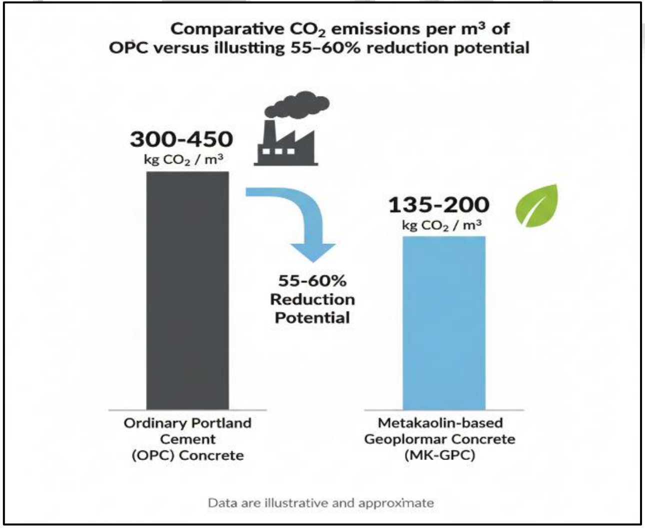


Microsurtcural schematic showing formation of N–A–S–H gel bridging MK particles, improving matrix density

V. ENVIRONMENTAL CHALLENGES AND SUSTAINABILITY

MK-GPC production emits 250–300 kg CO_2 per tonne of concrete, compared with ~900 kg for OPC concrete. This 60–70% reduction stems from lower calcination temperatures and absence of clinkerization. However, sodium silicate and sodium hydroxide production remain energy-intensive, contributing up to 40% of total emissions. Lifecycle analyses (Gupta et al., 2023) indicate that replacing synthetic activators with waste-derived alkalis (rice husk ash silica, soda ash) can reduce embodied energy by 18–25%.

Energy demand for MK calcination (~2.8 GJ/tonne) is significantly less than OPC (~5.4 GJ/tonne). Global warming potential analyses reveal MK-GPC's embodied CO_2 intensity of 270–320 kg CO_2-eq/m^3, whereas OPC concrete exceeds 700 kg CO_2-eq/m^3.



Comparative CO_2 emissions per m^3 of OPC versus illustting 55–60% reduction potential

Data are illustrative and approximate

Recycling potential is another advantage: geopolymer concrete exhibits strong alkali stability, allowing it to be crushed and reused as reactive aggregate. Long-term studies predict a lifespan extension of 1.5× over OPC structures, further amplifying its environmental benefits.

VI. CONCLUDING REMARKS AND FUTURE SCOPE

Metakaolin-based geopolymer concrete demonstrates clear mechanical and environmental superiority over traditional cement-based systems. Strengths exceeding 70 MPa, high chemical resistance, and up to 60% CO_2 reduction have been consistently reported. Despite its advantages, challenges persist in ensuring activator sustainability and industrial scalability. Future research should focus on:

1) Developing low-alkali or hybrid activators derived from waste sources.
2) Enhancing predictive modeling of strength using AI-driven algorithms.
3) Studying long-term durability under variable temperature and humidity.
4) Establishing standardized guidelines for mix design and field performance evaluation.

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