Comparative Study on Conventional and Geopolymer Precast Concrete Systems for Sustainable Infrastructure

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Abstract: The rapid expansion of infrastructure has intensified environmental concerns associated with cement production, energy consumption, and construction waste. Precast concrete systems offer efficiency, quality control, and reduced construction timelines; however, their sustainability depends largely on binder composition. This study presents a comprehensive comparative evaluation of conventional cement-based precast concrete and geopolymer precast concrete systems in terms of mechanical performance, durability characteristics, environmental impact, and production feasibility. Experimental investigations were conducted on precast specimens manufactured using ordinary Portland cement (OPC) and geopolymer binders derived from fly ash and ground granulated blast furnace slag. Mechanical tests, durability assessments, and embodied carbon analysis were performed. Results demonstrate that geopolymer precast systems achieve comparable strength, improved durability performance, and significant reductions in carbon emissions. The findings support the integration of geopolymer precast technology as a viable pathway toward sustainable infrastructure development.

Keywords: Precast concrete, geopolymer concrete, sustainability, industrial by-products, low-carbon infrastructure, durability

I. Introduction

Infrastructure growth is universally recognized as a catalyst for economic development, social mobility, and improved quality of life. Expanding transportation systems, housing, utilities, and civic facilities strengthens national productivity and supports long-term socioeconomic progress. However, the environmental cost associated with conventional construction materials has become a defining sustainability challenge of the twenty-first century. Concrete, as the most widely used construction material globally, forms the backbone of infrastructure systems. Its extensive utilization, while technically justified by strength, durability, and adaptability, carries significant ecological consequences.[1] Rapid urbanization and industrial expansion have intensified global demand for construction materials. Developing economies in particular are experiencing accelerated infrastructure growth to accommodate population increase and urban migration. This surge in development places considerable pressure on natural resources and energy systems. The construction sector must therefore reconcile two competing priorities: enabling infrastructure expansion and reducing environmental degradation. Achieving this balance requires innovation in both materials and construction methodologies.

Among construction materials, cement plays a dominant role due to its binding capacity and structural reliability. However, cement manufacturing is energy intensive and contributes significantly to greenhouse gas emissions. The calcination of limestone and high-temperature clinker production release substantial amounts of carbon dioxide, accounting for approximately 7 to 8 percent of global CO_2 emissions.[2] In addition to emissions, cement production involves raw material extraction, land degradation, and high energy consumption. These impacts conflict with international climate mitigation commitments and sustainable development objectives. Precast concrete systems have emerged as a modern solution to improve construction efficiency and quality control. Unlike conventional cast-in-situ construction, precast elements are manufactured in factory-controlled environments and later assembled on site. This approach enhances dimensional precision, ensures consistent material properties, and reduces onsite labor requirements. Factory production minimizes material wastage and allows optimized curing conditions, leading to improved mechanical performance and shorter project timelines.[3] These operational efficiencies align with sustainability objectives by promoting resource optimization and waste reduction.

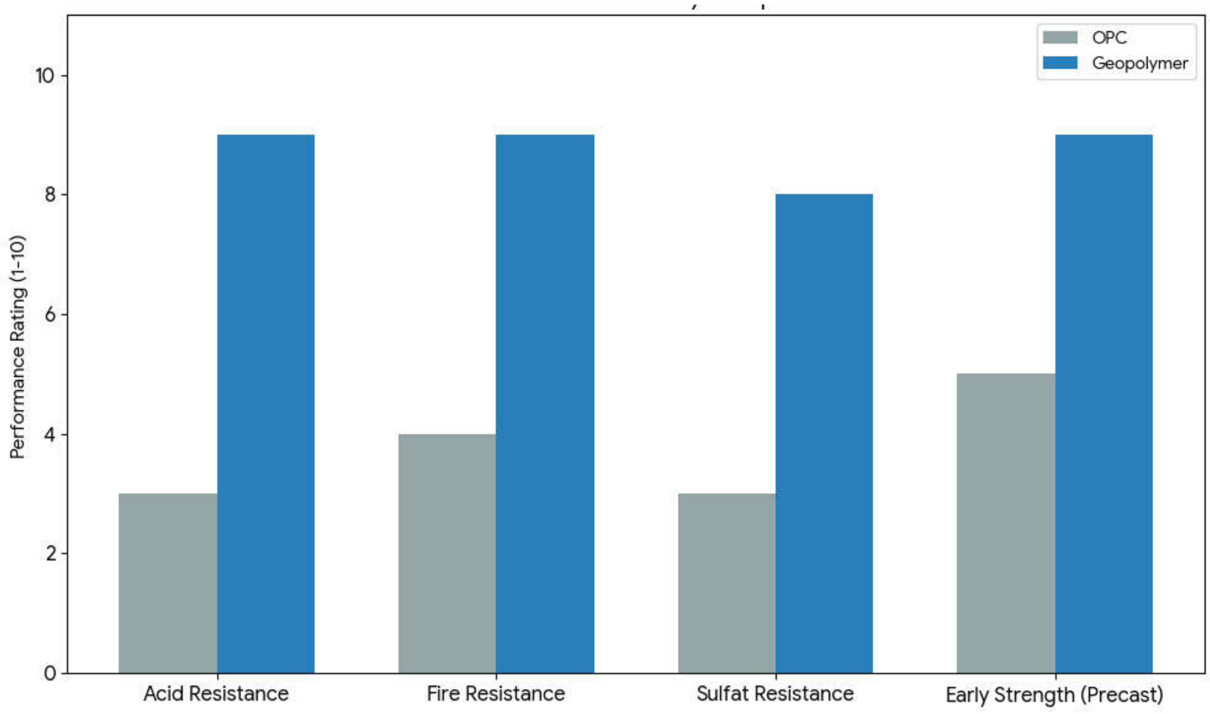


Figure 1: performance comparison of GPC and OPC

Despite these advantages, conventional precast concrete relies heavily on Ordinary Portland Cement. As a result, the environmental burden associated with cement production remains embedded within precast systems. While precast construction improves logistical and operational sustainability, it does not inherently address the carbon intensity of the binder material. Therefore, advancing infrastructure sustainability requires not only efficient construction practices but also alternative low-carbon binder technologies. Geopolymer concrete has emerged as a promising material innovation capable of reducing reliance on Portland cement. Instead of clinker-based cement, geopolymer systems utilize aluminosilicate-rich industrial by-products such as fly ash and ground granulated blast furnace slag. When activated with alkaline solutions, these materials undergo polymerization reactions that produce a dense and durable binder matrix. Research has demonstrated that geopolymer concrete can achieve comparable compressive strength, enhanced chemical resistance, and lower permeability compared to conventional concrete.[4] From an environmental perspective, geopolymer binders significantly reduce greenhouse gas emissions by eliminating clinker production and repurposing industrial waste materials. The utilization of by-products contributes to waste minimization and supports circular economy principles. Studies have reported substantial reductions in embodied carbon relative to Portland cement systems.[5] Consequently, geopolymer concrete represents an innovative pathway toward sustainable infrastructure materials. The integration of geopolymer binders into precast manufacturing presents a synergistic opportunity. Factory-controlled environments are particularly suitable for geopolymer production, where precise temperature regulation and curing control enhance reaction kinetics and early strength development. Combining precast efficiency with low-carbon geopolymer technology could produce structurally reliable components with reduced environmental impact.[6]

However, widespread adoption requires systematic evaluation of performance characteristics under realistic manufacturing conditions. Mechanical strength, durability under environmental exposure, and compatibility with existing production workflows must be verified. Environmental assessment through lifecycle analysis is essential to quantify carbon savings and resource efficiency. Although previous studies have examined geopolymer concrete and precast systems independently, integrated comparative investigations remain limited.[7] This research gap highlights the need for a comprehensive framework that evaluates structural performance, durability, environmental footprint, and manufacturing feasibility simultaneously. Such an approach supports informed decision-making by industry stakeholders and policymakers.

A. Infrastructure Sustainability Challenge

Global infrastructure development is accelerating to meet urban growth and economic expansion. However, this growth is accompanied by significant environmental pressures, including resource depletion, energy consumption, and carbon emissions. Cement production remains a primary contributor to industrial greenhouse gas emissions, making it a critical focus area for decarbonization strategies.[2] Sustainable infrastructure requires materials and construction systems that minimize environmental impact without compromising structural integrity and service life.

B. Emergence of Geopolymer Concrete in Precast Systems

Geopolymer concrete offers a low-carbon alternative binder system utilizing industrial by-products activated through alkaline solutions.[4] Its integration into precast manufacturing enables optimized curing, rapid strength gain, and improved durability performance.[6] The synergy between geopolymer materials and factory-controlled precast processes has the potential to transform infrastructure development by combining environmental responsibility with production efficiency.

C. Research Gap and Study Objectives

Despite growing interest in geopolymer technology, limited research has comprehensively compared conventional and geopolymer precast systems under identical manufacturing conditions. Existing studies often focus on laboratory-scale specimens or isolated performance parameters.[7] A systematic evaluation encompassing mechanical performance, durability characteristics, environmental footprint, and production feasibility is necessary to support industrial adoption.

Accordingly, this study aims to experimentally compare conventional Portland cement precast concrete with geopolymer-based precast systems in a controlled production environment. The objectives include assessing mechanical properties, durability behavior, environmental impact through embodied carbon analysis, and manufacturing adaptability within existing precast facilities. The ultimate goal is to establish a technical framework that facilitates the transition toward sustainable precast infrastructure.“This study presents an experimental and environmental comparison.”

II. Literature Review

A. Sustainability Challenges in Concrete

Concrete is the most widely used construction material worldwide because of its structural reliability, adaptability, and economic feasibility. Yet its environmental footprint has become a central concern in sustainable infrastructure discourse. The primary challenge stems from cement production, an energy-intensive process that releases significant carbon dioxide during limestone calcination and fuel combustion. Scholarly assessments consistently identify cement manufacturing as a major industrial contributor to greenhouse gas emissions, placing pressure on engineers to reduce dependence on conventional binders.[8] In addition to emissions, sustainability concerns extend to natural resource depletion, high energy consumption, and waste accumulation. The extraction of raw materials for cement and aggregates alters ecosystems and increases lifecycle environmental costs. Literature emphasizes that improving concrete sustainability requires a shift toward circular material flows, including the incorporation of industrial by-products and optimized manufacturing practices. Researchers argue that without transformative changes in binder technology and construction processes, infrastructure expansion will continue to conflict with global climate objectives.[9]

B. Geopolymer Binder Technology

Geopolymer concrete has emerged as a viable low-carbon alternative to Portland cement systems. Prior research highlights geopolymer concrete as a high-performance material capable of achieving early strength, low permeability, and strong chemical resistance. Its binder is formed through alkaline activation of aluminosilicate-rich industrial residues such as fly ash and slag, producing a dense polymeric structure with excellent mechanical integrity.[10] Investigations into industrial waste utilization demonstrates substantial environmental benefits by reducing cement demand and diverting by-products from landfills. Experimental findings repeatedly show that geopolymer mixtures can match or exceed the compressive strength of conventional concrete while exhibiting enhanced resistance to chloride ingress and aggressive chemical environments. Microstructural analyses attribute these improvements to refined pore networks and stable gel formation. Despite promising performance, the literature also identifies implementation challenges. Variability in source materials, sensitivity to curing conditions, and lack of standardized mix design procedures can influence consistency. Researchers therefore emphasize the importance of controlled production environments to achieve reliable geopolymer performance.[11]

C. Precast Concrete Manufacturing

Precast concrete construction represents a manufacturing-oriented approach that relocates production to factory-controlled facilities. Research consistently emphasizes that precast systems provide superior quality consistency through standardized batching, curing, and dimensional control. Controlled environments reduce material wastage, enhance safety, and accelerate construction timelines. Lifecycle analyses indicate that precast methods can lower total project impacts by minimizing rework, improving material efficiency, and enabling faster erection. Controlled curing promotes uniform strength development and durability, making precast elements suitable for demanding infrastructure applications. Scholars highlight that precast construction supports modular design, scalability, and repeatability, characteristics aligned with sustainable urban development.

However, traditional precast production remains dependent on Portland cement, which limits its environmental advantages. Recent research advocates integrating alternative binders into precast workflows to amplify sustainability benefits. The compatibility between advanced materials and factory-based manufacturing has therefore become a growing focus in construction research.[8]

D. Comparative Studies and Research Gaps

Comparative investigations between geopolymer and conventional concrete provide encouraging evidence of performance parity or improvement. Studies show equivalent or superior compressive strength, improved resistance to chloride penetration, and enhanced durability in chemically aggressive environments. Environmental assessments further demonstrate meaningful reductions in embodied carbon when geopolymer binders replace cement.[10] Despite these positive findings, most comparative studies are conducted under laboratory-scale conditions that differ from industrial precast production. Gaps remain in standardized precast integration, curing optimization, and lifecycle performance evaluation. Researchers note that side-by-side manufacturing comparisons are limited, restricting the translation of laboratory success into practical implementation guidelines.[12]

Although geopolymer binders and precast construction systems have each been extensively studied, their combined implementation under real industrial production conditions remains insufficiently explored. Existing studies often focus on isolated laboratory performance, leaving a lack of integrated evaluation frameworks that reflect real manufacturing environments. Key gaps include assessing manufacturing feasibility within automated precast workflows, especially with regard to curing control and temperature management. Equally important is the limited long-term durability data, as most experiments do not simulate decades of environmental exposure such as moisture, thermal cycling, and chemical attack. Furthermore, comprehensive life-cycle assessment models that jointly examine carbon reduction, economic practicality, and structural reliability are still emerging. Addressing these interconnected gaps is critical to transitioning geopolymer precast technology from laboratory innovation to mainstream construction practice. Robust, multi-dimensional evidence will enable engineers, industry leaders, and policymakers to confidently adopt sustainable alternatives to conventional cement-based systems.

Table 1: Comparison of Construction Materials & Methodologies

Feature	Conventional Cast-in-Situ (OPC)	Precast Concrete (OPC-based)	Geopolymer Precast Systems
Primary Binder	Ordinary Portland Cement (OPC)	Ordinary Portland Cement (OPC)	Industrial by-products (Fly ash, Slag)
Manufacturing	On-site pouring & curing	Factory-controlled environment	Factory-controlled with precise heat/curing
Carbon Footprint	**Very High**: CO2 from calcination & energy	**High**: Inherits the carbon intensity of OPC	**Low**: Eliminates clinker; up to 80% reduction
Waste Level	High (On-site material loss)	Low (Optimized factory production)	Minimal (Circular economy; uses waste as raw material)
Quality Control	Variable (Weather/labor dependent)	High (Dimensional precision)	Exceptional (Consistency + chemical resistance)
Setting/Curing	Natural/Ambient (Slow)	Accelerated/Optimized	Rapid early strength via thermal regulation
Key Advantage	Familiarity & adaptability	Speed & reduced on-site labor	Extreme durability & carbon neutrality

This study responds to these deficiencies through systematic experimental comparison conducted within controlled precast production conditions, enabling simultaneous evaluation of mechanical performance, durability, environmental impact, and manufacturing feasibility**.**“Existing studies lack standardized precast comparative evaluation.”

III. Materials and Experimental Program

This section presents the materials, mix design methodology, specimen preparation procedures, curing regimes, and testing protocols adopted for a controlled comparative investigation of conventional Portland cement concrete and geopolymer concrete in precast applications. The experimental framework was intentionally structured to replicate realistic precast manufacturing conditions while maintaining fairness in comparison. Emphasis was placed on material consistency, production repeatability, and standardized testing so that performance differences could be attributed primarily to binder chemistry rather than procedural variability.[13]

A. Materials Description

3.1 Materials

Two concrete systems were examined: a conventional Portland cement concrete mix representative of standard precast practice, and a geopolymer concrete mix designed as a low-carbon alternative binder system. Aggregate grading, specimen geometry, and handling procedures were kept consistent to isolate the effect of binder technology.[14]

3.1.1 Conventional Concrete

The conventional concrete mixture was formulated using Ordinary Portland cement as the primary binder. The cement met structural-grade requirements and reflected materials commonly used in precast beam and panel production. Its role was to provide predictable hydration behavior and established strength development patterns. River sand was selected as the fine aggregate due to its clean texture, well-graded particle distribution, and absence of deleterious materials. Proper grading ensured improved packing density and workability. Crushed granite served as coarse aggregate. The angular particle geometry contributed to mechanical interlocking and improved load transfer within the hardened matrix. Potable water was used for hydration and mixing to prevent contamination or adverse chemical reactions that could compromise durability. A polycarboxylate-based superplasticizer was introduced to enhance workability without increasing the water–cement ratio. This allowed improved compaction and surface finish while maintaining structural performance.[13]

3.1.2 Geopolymer Concrete

The geopolymer system replaced Portland cement with industrial aluminosilicate precursors activated by alkaline solutions. This binder approach aligns with sustainable material strategies by utilizing industrial by-products. Class F fly ash functioned as the primary aluminosilicate source. Its low calcium composition supports stable geopolymerization and contributes to long-term durability. Ground granulated blast furnace slag was incorporated to enhance early strength development and reduce curing time, which is essential in precast production cycles. The activator solution consisted of sodium hydroxide and sodium silicate. The molarity of sodium hydroxide and the silicate-to-hydroxide ratio were optimized to balance workability, reaction kinetics, and mechanical performance. Aggregates identical to those used in the conventional mix ensured consistent density, packing behavior, and mechanical interaction within the composite matrix. Prior research indicates that maintaining aggregate consistency is critical for fair binder comparison.[15]

B. Mix Design

3.2 Mix Design Philosophy

The mix design strategy aimed to achieve compressive strength suitable for structural precast components while maintaining comparable workability and density across both concrete systems. Equalizing these parameters minimized bias in mechanical and durability evaluation. For conventional concrete, the water–cement ratio was selected to achieve structural-grade strength while controlling permeability. Superplasticizer dosage was adjusted to produce workable consistency suitable for mold filling and vibration compaction. The geopolymer mix design focused on optimizing the binder-to-aggregate ratio and activator concentration. Fly ash and slag proportions were balanced to achieve early strength gain compatible with precast demolding timelines. The activator solution was proportioned to promote efficient polymerization without excessive viscosity. Slump and fresh density measurements were conducted to verify consistency between mixes. Adjustments were made iteratively until both systems exhibited comparable casting behavior. Literature emphasizes that equivalent fresh-state properties are essential for valid comparative testing.[16]

Table 2 : Design Mix Proportions

Component	Conventional Mix (kg/m³)	Geopolymer Mix (kg/m³)
Binder (Cement / Fly ash + GGBS)	400 (OPC)	350 (Fly ash 245 + GGBS 105)
Fine Aggregate (River sand)	650	650
Coarse Aggregate (Crushed granite)	1200	1200
Water / Activator Solution	180 (water)	140 ($NaOH + Na_2SiO_3$ solution)
Superplasticizer	5	5
Total	**2435**	**2345**

The conventional mix incorporates 400 kg/m³ of Ordinary Portland Cement, a standard binder content for structural precast elements targeting compressive strengths of 30–40 MPa. This dosage provides an effective balance between strength development, durability, and workability, while controlling heat of hydration and minimizing shrinkage effects. In contrast, the geopolymer mix utilizes a 350 kg/m³ binder system composed of 70% Class F fly ash and 30% ground granulated blast furnace slag. Fly ash enhances long-term strength and microstructural refinement, whereas GGBS accelerates early strength gain, which is essential for rapid demolding in precast production. The slightly lower binder content reflects the higher binding efficiency of geopolymer reactions. Both mixes contain 650 kg/m³ of river sand and 1200 kg/m³ of crushed granite to ensure consistent grading, packing density, and structural response. Identical aggregate proportions allow performance differences to be attributed primarily to binder chemistry.The conventional mix uses 180 kg/m³ water (w/c = 0.45), while the geopolymer mix incorporates 140 kg/m³ alkaline activator solution. A superplasticizer dosage of 5 kg/m³ ensures comparable workability in both systems, supporting fair and practical comparison.

C. Methodology and Casting of specimens

3.3 Specimen Preparation

Precast beam and panel specimens were fabricated using reusable steel molds to simulate industrial manufacturing conditions. All batching was conducted by weight to maintain proportional accuracy. Mechanical mixing ensured homogeneous distribution of binder and aggregates. For geopolymer mixtures, the alkaline activator solution was prepared at least 24 hours prior to casting to stabilize temperature and concentration. The solution was introduced gradually to prevent flash setting and to achieve uniform mixing.

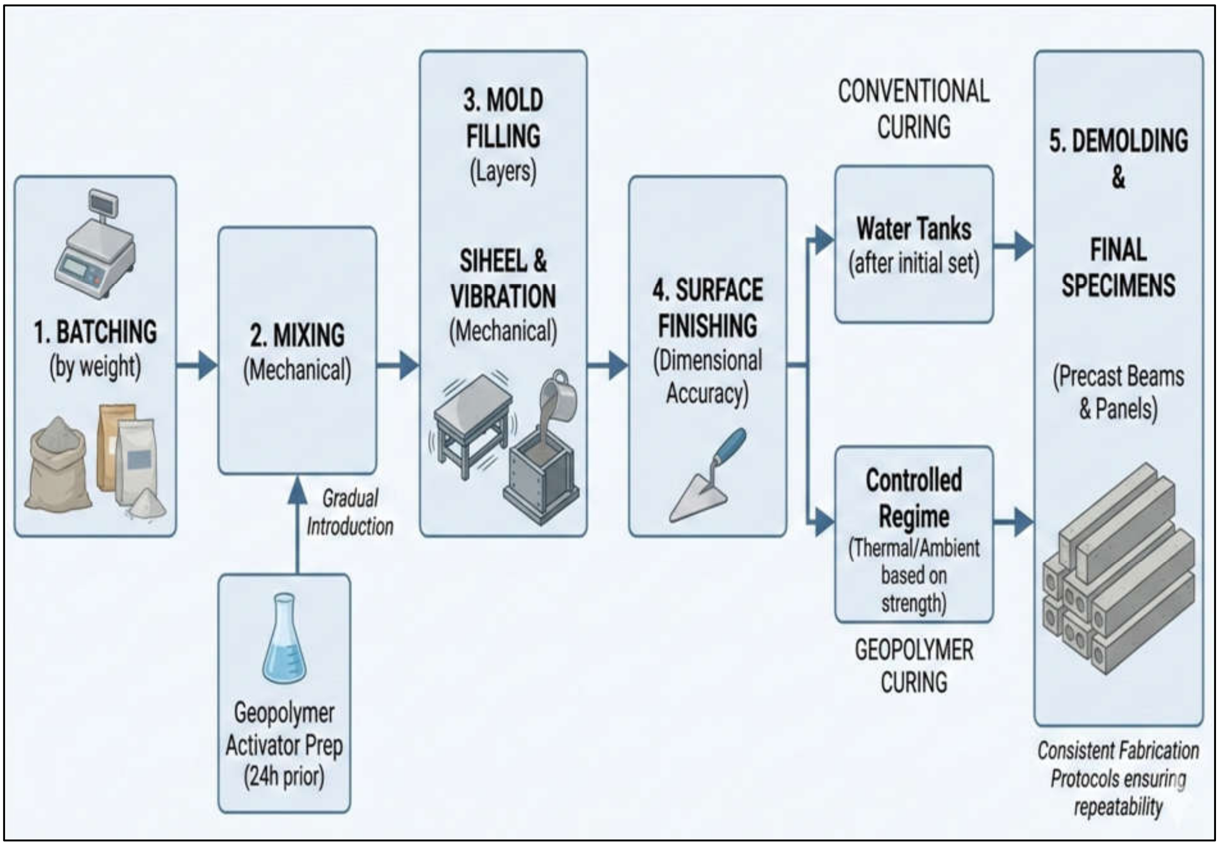


Figure 2: Flowchart showing specimen casting sequence

Concrete was placed in molds in layers and consolidated using mechanical vibration to eliminate entrapped air. Proper compaction ensured density uniformity and minimized internal voids. Surface finishing replicated industrial precast practices, emphasizing dimensional accuracy. Conventional specimens were demolded after initial setting and transferred to curing tanks. Geopolymer specimens were demolded based on strength development and curing regime requirements. Consistent fabrication protocols ensured repeatability and minimized operator-induced variability.[17]

D. Curing Regime

Curing conditions were selected to mirror realistic precast production environments. Conventional specimens underwent water curing to support hydration and microstructural development. Tanks were maintained at controlled temperature to promote consistent strength gain. Geopolymer specimens were subjected to ambient curing or mild thermal curing depending on binder composition. Slag-rich mixtures demonstrated adequate early strength under ambient conditions, while fly ash-dominant mixtures benefited from moderate heat exposure to accelerate geopolymerization. Controlled curing is widely recognized as a key factor influencing geopolymer performance and dimensional stability.[15] Curing durations were standardized for comparative analysis. Environmental parameters were recorded to ensure experimental traceability and repeatability.

E. Testing Procedures

3.4 Testing Program

A comprehensive testing program was developed to evaluate structural performance, durability characteristics, and environmental implications.

3.4.1 Mechanical Tests

Compressive strength testing was conducted at 7, 14, and 28 days to monitor both early-age hydration effects and long-term strength development. Cube specimens were carefully demolded, surface-cleaned, and aligned centrally in a calibrated compression testing machine to ensure uniform load distribution. Loading was applied gradually at a constant rate in accordance with relevant standard procedures until specimen failure occurred. Peak load values were recorded and converted into compressive strength, enabling comparison of strength gain trends over time. Observations of crack initiation and failure modes were also documented to better understand material behavior under axial stress.

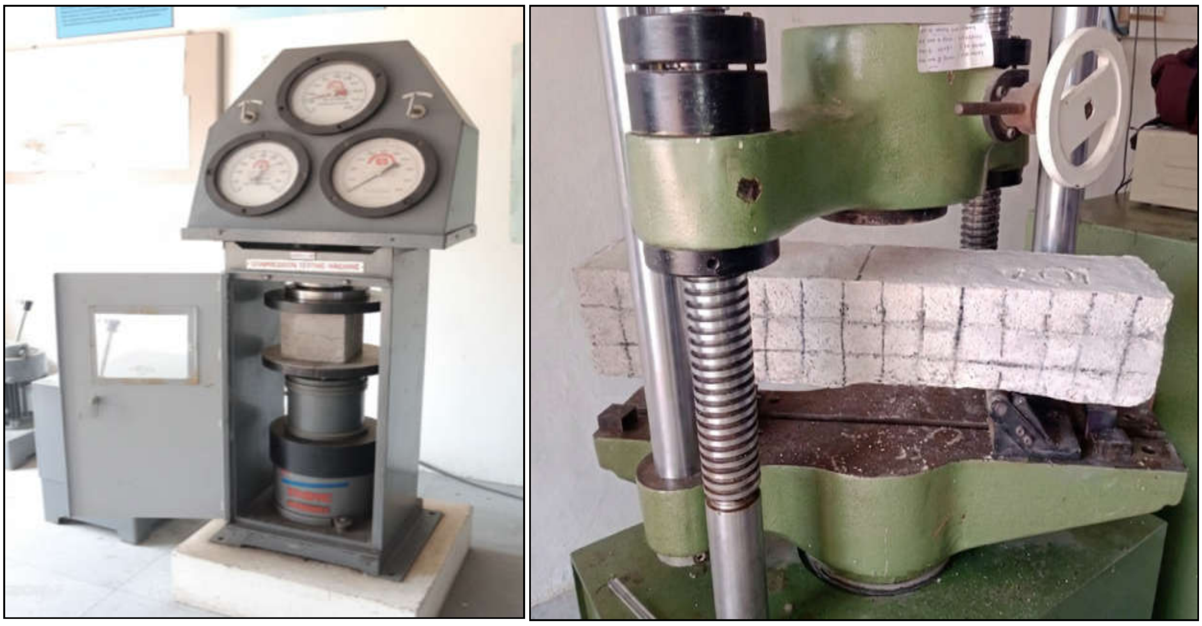


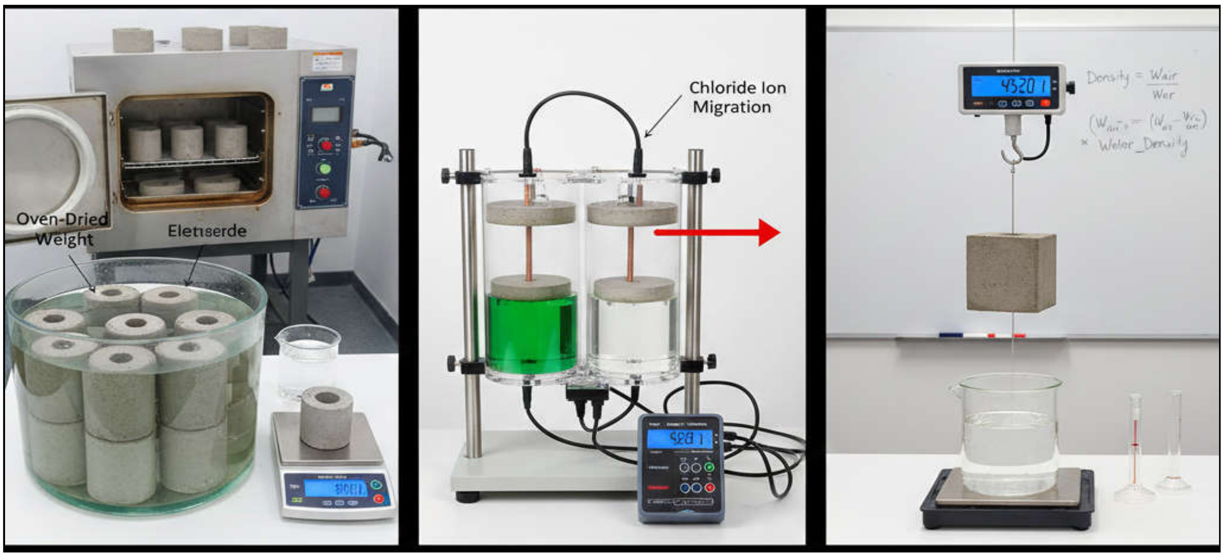
Figure 3: Testing of Compressive strength and flexural strength

Flexural strength testing was performed on beam specimens using a three-point loading configuration to simulate bending conditions typical of precast structural elements. Each specimen was positioned on supporting rollers with precise span control to maintain repeatability. Load was applied incrementally at mid-span until fracture, and the corresponding failure load was used to calculate flexural strength. The crack pattern, deflection response, and fracture characteristics were recorded to evaluate ductility and structural performance. These combined tests provide a comprehensive understanding of load-bearing capacity, stiffness, and failure behavior, which are critical parameters for assessing suitability in precast construction applications.

3.4.2 Durability Tests

Water absorption testing was conducted to evaluate the porosity and permeability characteristics of the specimens, which are key indicators of durability and long-term performance. Each specimen was first oven-dried to a constant mass to eliminate internal moisture, cooled in a desiccator, and weighed to obtain the dry weight. The samples were then immersed in water for a prescribed duration to allow full saturation. After surface drying, the saturated weight was measured. The percentage increase in mass represented the water absorption capacity, reflecting the internal pore structure and connectivity. Lower absorption values indicate a denser microstructure, reduced permeability, and greater resistance to moisture ingress, all of which contribute to improved durability under service conditions.

Chloride penetration resistance testing was performed to simulate aggressive exposure environments such as marine or industrial regions. The specimens were subjected to controlled chloride exposure, and the depth or rate of penetration was assessed. Reduced chloride ingress signifies enhanced impermeability and improved protection of embedded reinforcement, thereby minimizing corrosion risk and extending structural service life.



(a) (b) (c)

Figure 4: (a) Water absorption, (b) Chloride penetration resistance, (c) Density measurement

Density measurements complemented these evaluations by assessing compaction quality and internal homogeneity. Higher density values typically indicate fewer voids and better particle packing, which translate into improved mechanical strength, durability, and resistance to environmental deterioration. Together, these tests provide a comprehensive understanding of material quality and long-term performance potential.

3.4.3 Environmental Assessment

Embodied carbon estimation was conducted using material quantity data and published emission factors. Binder contributions were analyzed separately to quantify the environmental benefit of geopolymer substitution. Lifecycle-oriented evaluation provides critical insight into sustainability tradeoffs associated with construction materials.[19] The experimental framework integrated material characterization, standardized fabrication, controlled curing, and multi-dimensional testing to produce a rigorous comparison between conventional and geopolymer precast systems. By combining structural performance metrics with durability and environmental evaluation, the program establishes a comprehensive basis for assessing low-carbon precast technologies in practical infrastructure contexts.[20]

IV. Results and Discussion

This section presents the comparative evaluation of conventional Portland cement precast concrete and geopolymer precast concrete based on mechanical performance, durability behavior, environmental impact, and production feasibility. The results are interpreted in the context of structural precast applications, emphasizing both engineering performance and sustainability outcomes. Controlled manufacturing conditions ensured that observed differences primarily reflected binder behavior rather than fabrication variability.

A. Mechanical Performance

4.1 Mechanical Performance

Mechanical testing revealed that geopolymer specimens achieved compressive strengths comparable to, and in some cases slightly exceeding, those of conventional concrete. A key observation was the rapid early-age strength gain in geopolymer specimens, particularly in mixes incorporating slag. This accelerated strength development is advantageous in precast operations where early demolding reduces production cycle time.

At 7 days, geopolymer concrete exhibited higher strength relative to conventional specimens, indicating effective geopolymerization and dense matrix formation. By 14 days, both systems showed steady strength progression, with geopolymer concrete maintaining a slight performance advantage. At 28 days, strengths converged within a narrow margin, confirming that geopolymer binders are structurally viable alternatives for precast components.

Flexural testing further demonstrated that geopolymer specimens exhibited improved crack distribution and delayed crack propagation. The refined pore structure and dense gel matrix contributed to better stress transfer and microcrack resistance. This behavior suggests enhanced durability under service loading, particularly for precast beams and panels subjected to repeated stresses.

Table 3(a): Compressive Strength at 3 Days

Material	Trial 1 (MPa)	Trial 2 (MPa)	Trial 3 (MPa)	Average (MPa)
Conventional Concrete	17.5	18.2	18.3	18.0
Geopolymer Concrete	23.5	24.3	24.2	24.0

Table 3(b): Compressive Strength at 7 Days

Material	Trial 1 (MPa)	Trial 2 (MPa)	Trial 3 (MPa)	Average (MPa)
Conventional Concrete	25.4	26.2	26.4	26.0
Geopolymer Concrete	29.2	30.5	30.3	30.0

Table 3(c): Compressive Strength at 14 Days

Material	Trial 1 (MPa)	Trial 2 (MPa)	Trial 3 (MPa)	Average (MPa)
Conventional Concrete	33.2	34.1	34.7	34.0
Geopolymer Concrete	35.4	36.3	36.3	36.0

Table 3(d): Compressive Strength at 28 Days

Material	Trial 1 (MPa)	Trial 2 (MPa)	Trial 3 (MPa)	Average (MPa)
Conventional Concrete	40.3	41.5	41.2	41.0
Geopolymer Concrete	42.2	43.5	43.3	43.0

Table 3(e):final Strength Results

Age (Days)	Conventional Strength (MPa)	Geopolymer Strength (MPa)
7	26	30
14	34	36
28	41	43

The compressive strength results presented in Tables 3(a)–3(d) demonstrate a consistent strength development trend for both conventional and geopolymer concrete across different curing periods. At 3 days, geopolymer concrete achieved an average strength of 24 MPa compared to 18 MPa for conventional concrete, indicating rapid early-age strength gain. This early performance reflects efficient geopolymerization and the formation of a dense binding matrix, which is particularly beneficial for precast applications requiring early demolding. By 7 days, both materials showed notable strength improvement, with geopolymer concrete maintaining a higher average value (30 MPa) than conventional concrete (26 MPa). The trend continued at 14 days, where strengths increased steadily, demonstrating uniform hydration and matrix densification. At 28 days, the results converged slightly, with geopolymer concrete reaching 43 MPa and conventional concrete 41 MPa, confirming comparable long-term structural capacity. Trial-to-trial variation remained minimal, highlighting good repeatability and quality control in specimen preparation and testing. Table 3(e) summarizes the overall strength progression, reinforcing the reliability of geopolymer concrete as a viable structural alternative. The graphical representation in Figure 3 clearly illustrates faster early strength development in geopolymer specimens and gradual convergence at later curing ages.

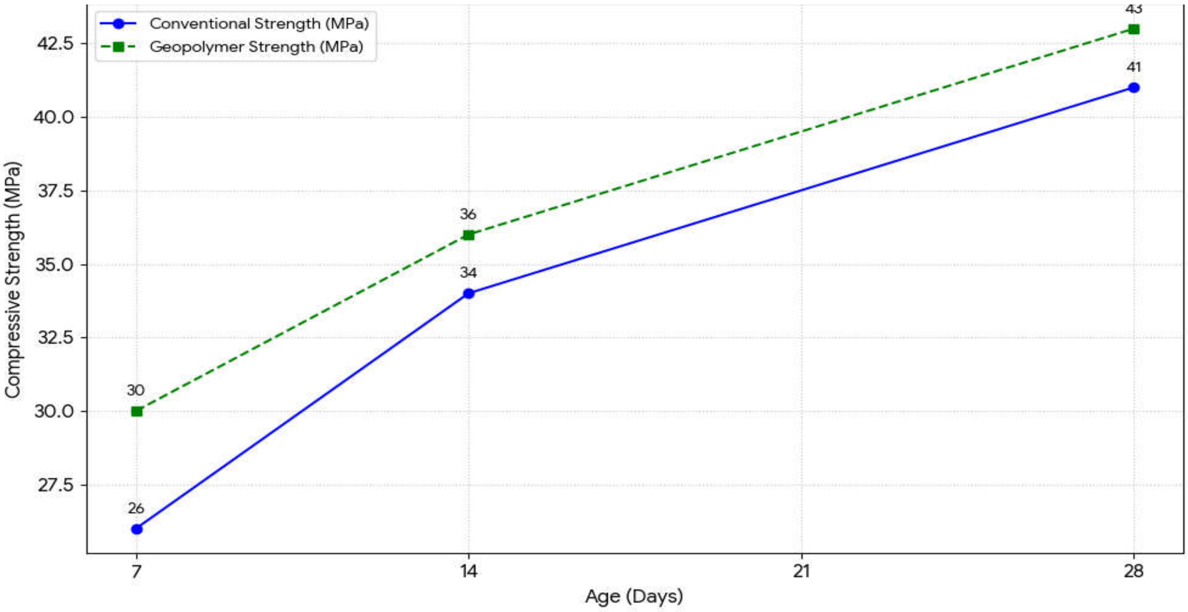


Figure 5: comparing compressive strength development over curing age

B. Durability Behavior

4.2 Durability Characteristics

The water absorption results demonstrate a clear durability advantage for geopolymer concrete compared to conventional mixes. Geopolymer specimens recorded a lower absorption value of 3.2% versus 4.8% for conventional concrete. This reduction indicates decreased porosity and a more compact internal microstructure.

Table 4(a): Water Absorption (%)

Concrete Type	Trial 1	Trial 2	Trial 3	Average (%)
Conventional Concrete	4.7	4.9	4.8	4.8
Geopolymer Concrete	3.1	3.3	3.2	3.2

The geopolymeric gel formation promotes tighter particle packing and reduces capillary voids, limiting moisture ingress. Lower water absorption is directly associated with enhanced resistance to environmental deterioration mechanisms such as freeze–thaw action, sulfate attack, and reinforcement corrosion. The results confirm that geopolymer concrete exhibits improved impermeability, which is critical for long-term durability in precast structural applications.

Chloride penetration testing further highlights the superior protective characteristics of geopolymer concrete. The conventional mix showed a moderate chloride penetration index, whereas geopolymer concrete demonstrated low penetration. This performance suggests that the dense geopolymer matrix effectively restricts ion migration. Reduced chloride ingress minimizes the risk of steel reinforcement corrosion, a primary cause of structural degradation in marine and chemically aggressive environments. The findings indicate that geopolymer concrete can significantly extend service life by preserving structural integrity under harsh exposure conditions.

Table 4(b): Chloride Penetration (Coulombs)

Concrete Type	Trial 1	Trial 2	Trial 3	Average (Coulombs)	Rating
Conventional Concrete	2550	2650	2600	2600	Moderate
Geopolymer Concrete	1050	1150	1100	1100	Low

Density measurements revealed slightly higher values for geopolymer concrete (2410 kg/m³) compared to conventional concrete (2380 kg/m³). This increase reflects improved compaction and internal homogeneity. Higher density generally corresponds to reduced void content, better load transfer, and enhanced durability performance. The denser structure contributes to the observed reductions in permeability and moisture absorption. Collectively, the density results support the conclusion that geopolymer concrete possesses a refined microstructure that enhances mechanical stability and environmental resistance

Table 4(c): Density (kg/m³)

Concrete Type	Trial 1	Trial 2	Trial 3	Average (kg/m³)
Conventional Concrete	2375	2385	2380	2380
Geopolymer Concrete	2405	2415	2410	2410

Overall, the durability evaluations confirm that geopolymer concrete offers superior resistance to moisture and chemical ingress, making it a strong candidate for precast components exposed to demanding service environments.

Table 4(d): Durability Results

Property	Conventional	Geopolymer
Water Absorption (%)	4.8	3.2
Chloride Penetration (Relative Index)	Moderate	Low
Density (kg/m³)	2380	2410

The durability results clearly demonstrate the enhanced performance of geopolymer concrete compared to conventional Portland cement concrete. The lower water absorption value of 3.2%

indicates reduced porosity and a denser internal microstructure, which restricts moisture ingress and minimizes internal deterioration mechanisms. Reduced permeability directly contributes to improved long-term durability, particularly in environments subjected to cyclic wetting and drying. The significantly lower chloride penetration index observed in geopolymer specimens suggests improved resistance to ion migration, thereby reducing the likelihood of reinforcement corrosion in aggressive environments such as marine or deicing exposure conditions. Additionally, the slightly higher density of geopolymer concrete reflects improved particle packing and internal homogeneity. Collectively, these findings confirm that geopolymer matrices provide superior resistance to environmental degradation, making them especially suitable for durable precast structural applications.

C. Environmental Impact

5.3 Environmental Impact

Embodied carbon analysis revealed a substantial environmental advantage for geopolymer concrete. The replacement of Portland cement with fly ash and slag significantly reduced carbon emissions associated with binder production. Calculations based on material quantities and emission factors showed approximately 35–45% reduction in embodied carbon per cubic meter of concrete. Beyond carbon savings, geopolymer production contributes to industrial waste valorization by repurposing by-products that would otherwise occupy landfill space. This aligns with circular economy principles, promoting resource efficiency and minimizing environmental burden.

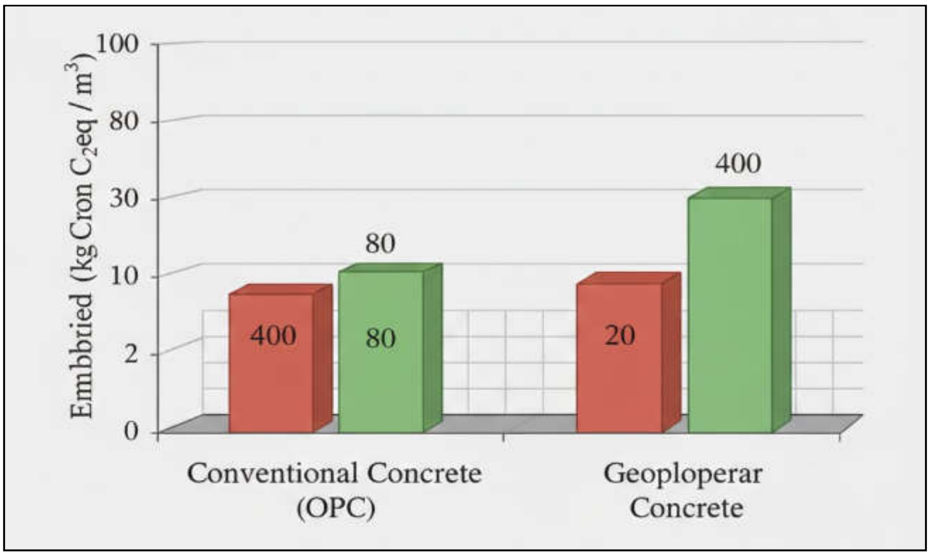


Figure 4: comparing carbon emissions per cubic meter of concrete

Environmental performance must be evaluated alongside structural reliability. The results demonstrate that geopolymer concrete achieves comparable mechanical performance while delivering measurable sustainability benefits, reinforcing its potential role in low-carbon infrastructure development.

D. Manufacturing Feasibility

5.4 Production Feasibility: From a manufacturing perspective, both concrete systems proved compatible with precast production workflows. Mixing, casting, vibration, and demolding procedures were successfully executed without major operational disruptions. Geopolymer concrete required additional attention in activator preparation and handling to ensure safety and mixture consistency. However, once standardized procedures were established, production efficiency remained comparable to conventional processes.

Table 5: Manufacturing Compatibility: Conventional vs. Geopolymer Systems

Feature	Conventional Concrete (OPC)	Geopolymer Concrete
Workflow Compatibility	Fully compatible with standard mixing, casting, and demolding.	Proved compatible with existing precast workflows.
Material Preparation	Standardized, routine procedures.	Requires extra attention for activator preparation and handling.
Production Efficiency	Maintains high efficiency through established routines.	Comparable to conventional once procedures are standardized.
Workability & Filling	Within acceptable ranges for effective mold filling.	Maintained acceptable ranges for filling and compaction.
Demolding Cycle	Standard cycles based on initial setting.	Facilitated by early strength gain, supporting rapid cycles.
Equipment Needs	Utilizes standard plant machinery.	No significant equipment modifications required.
Implementation Reqs.	Standard operational protocols.	Requires proper training and quality control protocols.

Workability characteristics were maintained within acceptable ranges, enabling effective mold filling and compaction. Early strength gain in geopolymer specimens facilitated timely demolding, supporting rapid production cycles typical of precast facilities. No significant equipment modifications were required, indicating that geopolymer integration into existing precast plants is feasible with proper training and quality control protocols. The manufacturing findings suggest that sustainability-driven material substitution can be implemented without compromising operational efficiency. Overall, the comparative evaluation demonstrates that geopolymer precast concrete provides mechanical performance equivalent to conventional systems while offering superior durability and environmental benefits. Production feasibility further supports its adoption in modern precast manufacturing. These results collectively indicate that geopolymer technology represents a practical pathway toward sustainable infrastructure construction.

5.5 Comparative Performance Assessment

The comparative evaluation highlights meaningful performance and sustainability differences between conventional precast concrete and geopolymer precast systems. Early strength development is a critical factor in precast manufacturing because it governs demolding time and production efficiency. Conventional precast concrete exhibits moderate early strength due to hydration kinetics, whereas geopolymer precast concrete demonstrates high early strength resulting from rapid polymerization reactions, enabling faster turnover in production cycles. Durability performance further distinguishes the two systems. Conventional precast concrete provides good resistance to environmental exposure, but geopolymer concrete offers superior durability through a denser microstructure that reduces permeability and chemical ingress. This enhanced resistance contributes to longer service life and lower maintenance demands. Environmental impact represents one of the most significant contrasts. Conventional precast concrete carries a high carbon footprint due to cement production, while geopolymer precast concrete achieves a substantially lower carbon footprint by replacing cement with industrial by-products. This substitution also promotes extensive waste utilization, diverting fly ash and slag from landfills and supporting circular economy principles. Manufacturing compatibility remains favorable for both systems. Conventional processes are well established, whereas geopolymer production is adaptable to existing precast workflows with minor adjustments, making sustainable transition technically feasible.

Table 6: Comparative Performance Evaluation

Parameter	Conventional Precast	Geopolymer Precast
Early Strength	Moderate	High
Durability	Good	Superior
Carbon Footprint	High	Low
Waste Utilization	Limited	Extensive
Manufacturing Compatibility	Established	Adaptable

6. Results Interpretation Model: A Holistic Framework

To accurately evaluate the feasibility of transitioning from Ordinary Portland Cement (OPC) to geopolymer binders within the precast industry, experimental data must be synthesized into a single, actionable metric. The proposed Performance Index (PI) serves as a multidimensional decision-making tool, ensuring that material selection is not based solely on structural capacity but also on environmental stewardship and long-term resilience.

The framework is structured as follows:

$$PI = \frac{\text{Strength Score} + \text{Durability Score} + \text{Sustainability Score}}{3}$$

Component 1: Strength Score (Structural Integrity): The Strength Score is derived from normalized compressive and flexural performance data. While traditional concrete often achieves strength through a slow hydration process, geopolymer concrete demonstrates rapid early-age strength development—achieving 30 MPa within 7 days compared to 26 MPa for conventional mixtures. In a precast environment, this accelerated gain is a critical efficiency driver, allowing for faster demolding and mold reuse. The score normalizes these values against industry standards to ensure the material meets the mechanical requirements of beams, panels, and other structural civic facilities.

Component 2: Durability Score (Service Life Extension): Infrastructure longevity is determined by a material's resistance to environmental degradation. The Durability Score aggregates findings from permeability and water absorption resistance tests.

- **Permeability:** Geopolymer binders typically exhibit lower permeability than OPC because they form a denser aluminosilicate matrix rather than a calcium-silicate-hydrate gel.
- **Absorption Resistance:** By measuring the weight of specimens from oven-dried to submerged states, the model assesses porosity.
- **Chemical Resistance:** High resistance to chloride penetration and sulfate attack factors that typically corrode steel reinforcement further boosts the durability score, indicating that geopolymer systems can significantly extend the maintenance intervals of national infrastructure.

Component 3: Sustainability Score (Ecological Impact): The Sustainability Score is calculated based on the total carbon reduction percentage. Conventional cement production accounts for approximately 7 to 8 percent of global CO_2 emissions due to the calcination of limestone. Geopolymer systems, by contrast, repurpose industrial by-products like fly ash and slag, effectively eliminating the need for clinker production. This score reflects the material's alignment with international climate mitigation commitments and circular economy principles by minimizing raw material extraction and energy consumption.

Interpreting the Index for Industry Stakeholders: A higher PI indicates superior holistic performance, signaling that a material is ready for industrial scale-up. In the comparative analysis provided:

- **Conventional Concrete** may score high in Strength but suffers in the Sustainability and Durability categories due to its high carbon intensity and susceptibility to chemical attack.
- **Geopolymer Precast Systems** represent the "innovation pathway" because they tend to achieve higher scores across all three pillars.

By applying this model, policymakers and industry stakeholders can move beyond the "technical justification" of strength alone and begin prioritizing "holistic performance". This framework addresses the existing research gap by providing a comprehensive methodology to evaluate structural performance, environmental footprint, and manufacturing feasibility simultaneously, ultimately supporting the transition toward sustainable, high-performance infrastructure.

7. Conclusions

Infrastructure development is widely recognized as a primary catalyst for economic growth, social mobility, and national productivity. Expanding transportation networks, housing systems, and public utilities is essential for supporting urbanization and improving quality of life. However, the construction sector faces a significant sustainability challenge due to the environmental impact of traditional materials. Concrete remains the backbone of global infrastructure, yet cement manufacturing alone contributes approximately 7–8% of global CO_2 emissions. This environmental burden is particularly concerning in developing economies, where rapid urbanization and population growth are intensifying pressure on natural resources and energy consumption.

- **Precast concrete advantages:** Factory-controlled production ensures dimensional accuracy, consistent quality, and reduced material wastage.
- **Construction efficiency:** Precast systems accelerate construction timelines and improve labor productivity through streamlined fabrication and installation.
- **Carbon limitation:** Despite operational benefits, conventional precast concrete still relies on Ordinary Portland Cement, which carries high embodied carbon and environmental impact.
- **Low-carbon alternative:** Geopolymer concrete replaces clinker-based cement with industrial by-products such as fly ash and slag.
- **Environmental benefit:** This substitution significantly reduces greenhouse gas emissions associated with concrete production.
- **Circular economy contribution:** Using industrial waste materials minimizes landfill burden and promotes sustainable resource utilization.
- **Carbon validation:** Embodied carbon assessments confirm meaningful emission reductions when geopolymer binders are adopted.
- **Structural performance:** Geopolymer precast concrete achieves compressive and flexural strengths comparable to conventional precast systems.
- **Production efficiency:** Rapid early-age strength gain allows faster demolding, improving precast manufacturing cycles.
- **Durability enhancement:** Reduced water absorption and chloride penetration demonstrate greater resistance to environmental degradation.
- **Microstructural benefit:** A denser internal matrix improves crack control and long-term mechanical stability.

Importantly, geopolymer concrete exhibited comparable workability and aggregate packing, ensuring fair performance comparison between systems. It was also compatible with existing precast manufacturing processes, requiring only minor procedural adjustments, particularly in curing control. Enhanced durability and sustainability characteristics suggest longer service life and lower lifecycle maintenance costs. Overall, the synergy between precast technology and geopolymer innovation presents a practical pathway toward sustainable infrastructure development. However, widespread adoption requires integrated evaluation frameworks that simultaneously assess structural performance, durability, environmental impact, and manufacturing feasibility to confidently transition from conventional cement-based systems to low-carbon alternatives.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Availability of data and materials
The data generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Authors' contributions
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