

Sustainable Concrete Solutions: Chemically Predictive Modeling of Geopolymer Versus Ordinary Concrete in a Circular Economy

Akshay Dhawan¹, Manvendra Verma^{2,*}

Abstract

Concrete is a fundamental structural material widely used in civil engineering projects. It plays a key role in various types of building structures, with its quality directly influencing the durability of the construction. This research focuses on assessing the current state of concrete construction, highlighting critical issues and technical aspects in the process, while emphasizing the importance of improving construction quality and management practices. Geopolymer concrete (GPC) presents a viable solution for mitigating structural degradation and addressing environmental issues. Nonetheless, there has been a paucity of research regarding its financial implications. This study investigates the GPC production utilising by-products of industrial, specifically GGBFS and fly ash. Source materials are activated with alkaline solutions that vary in concentration and composition, especially regarding the proportion of GGBFS. A major objective of this research is to evaluate the economic viability and production cost of GPC in comparison to conventional ordinary Portland cement (OPC) concrete. The results indicate that although some GPC mixes (e.g., GPC-2 and GPCS-7) may have a lower economic index than OPC, their production costs are significantly reduced—by 31.13% and 43.74%, respectively. Furthermore, GPC demonstrates improved compressive strength compared to OPC, reinforcing its potential as a more cost-effective and practical alternative in construction applications.

Keywords: Geopolymer concrete; cement chemistry; compressive strength; circular economy; predictive modelling

INTRODUCTION

In recent years, civil engineering construction projects have increasingly relied on concrete as a fundamental base material. This preference stems from the inherent advantages of concrete over other building materials, making it irreplaceable in many applications. Moreover, the technological advancement in concrete construction significantly affects the overall quality and efficiency of construction practices [1–6]. As China's civil infrastructure has expanded rapidly, concerns regarding construction quality have gained growing public attention [7,8]. The safety and performance of concrete structures are directly linked to both public welfare and the economic interests of construction firms.

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Although concrete offers multiple advantages, its performance is highly sensitive to construction practices. Poor control over the constituent materials and mishandling during the building process can lead to significant quality deterioration [9,10].

Ordinary Portland Cement (OPC) is the most widely used binder in construction, and its bonding capability is deeply rooted in its complex chemical reactions. The primary chemical process that governs the hardening and strength development of OPC is hydration—a reaction between cement compounds and water. When water is added to

OPC, it reacts with four main clinker minerals: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) [11]. These reactions lead to the formation of calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$), both of which are critical to the development of strength and durability in concrete. C-S-H acts as the primary binding phase that glues the aggregates together and fills the voids, giving the concrete its rigidity and load-bearing capacity. Additionally, the formation of ettringite and other hydration products contributes to volume stability and early strength. Thus, the bonding power of OPC cement is a result of intricate chemical transformations that turn a dry powder into a rock-like solid, enabling the construction of resilient and long-lasting structures [12].

Over the past few decades, geopolymer concrete (GPC) has emerged as a high-durability alternative to ordinary Portland cement (OPC) concrete. GPC is typically synthesized using alkaline solutions and aluminosilicate-rich source materials such as ground granulated blast furnace slag (GGBFS), fly ash, and metakaolin (MK) [13,14]. These alkali-activated binders are seen as potential solutions to the twin challenges of construction waste and environmental degradation. Current research increasingly favors low-calcium source materials, as calcium-rich sources like slags are limited in availability. The term "geopolymer" was first introduced by Joseph Davidovits in 1978 [15]. These inorganic polymers are formed through a polycondensation reaction between alkaline activators and aluminosilicate-rich industrial by-products [16,17]. Geopolymer formation involves the combination of silicate $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ tetrahedra, resulting in a three-dimensional aluminosilicate network. This structure transitions from an amorphous to a semi-crystalline phase. The substitution of silicon by aluminum in the tetrahedral framework is balanced by alkali cations (e.g., Na^+), ensuring electrical neutrality [13,18].

Despite growing interest, the precise mechanisms governing geopolymer formation and hardening remain somewhat ambiguous. During geopolymerization, aluminosilicate raw materials dissolve in alkaline solutions, releasing silicate and aluminate monomers [19,20]. These monomers undergo dissolution, condensation, polymerization, and structural rearrangement. As shown in Figure 1, this sequence leads to the formation of larger oligomeric and polymeric structures through the reorganization of dissolved aluminosilicates [21].

When oligomers form bonds, hydroxyl (OH) groups at their ends combine, releasing water and redistributing oxygen atoms in the process. Many historical structures constructed with geopolymers are composed primarily of TO_4 tetrahedrons (where T represents silicon or aluminium) as the fundamental building blocks [22]. Geopolymer cement concrete (GPC), with its excellent engineering properties, is considered a promising alternative to ordinary Portland cement (OPC) concrete [23]. Often referred to as "green concrete," GPC offers significant environmental benefits. It effectively utilizes industrial by-products, conserves natural resources, and notably reduces CO_2 emissions, addressing key environmental and sustainability challenges within the cement and construction industries [24].

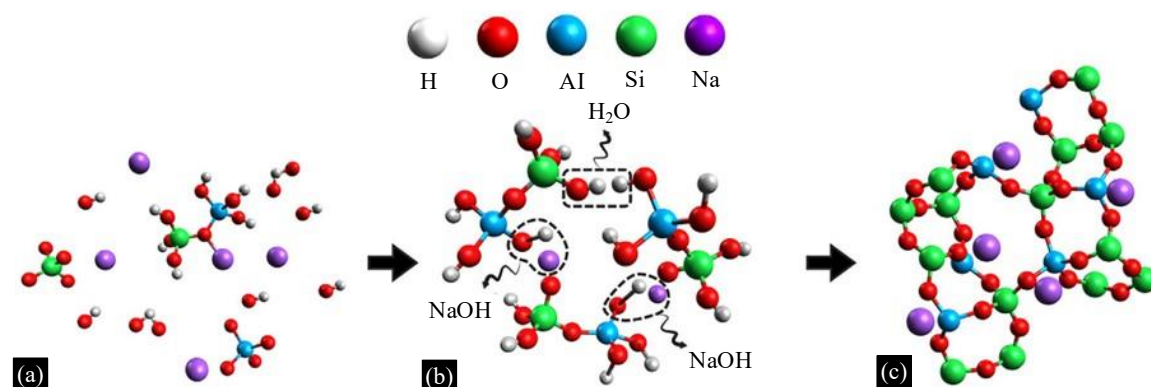


Figure 1. Geopolymerisation process a) aluminosilicate restructuring, b) gel formation, and c) polymerization.

To highlight its potential applications in modern construction, this study thoroughly reviews the existing literature, exploring the geopolymerization process, water absorption methods, material characterization techniques, and the overall properties of GPCs [25]. The approach to mix design in GPC is guided not only by its macro and microstructural properties but also by soil behavior and geotechnical factors, such as load-bearing capacity and soil-structure interaction. These considerations directly influence the serviceability and performance of foundations and structural elements [26].

Enhancing foundation behavior through proper soil improvement methods allows for better control over parameters such as shear response, deflection, applied forces, and time to failure in structural members. The seismic performance of structures is also closely tied to the behavior of the underlying soil, highlighting the importance of a stable foundation in resisting dynamic loads [27]. Geopolymers belong to the class of mineral polymers and exhibit a predominantly amorphous microstructure, distinct from crystalline forms. Chemically, their composition closely resembles that of zeolites. GPC is formed using polymeric binders—such as alkaline activators—and can serve as a viable replacement for OPC. Many researchers advocate for GPC as a sustainable substitute for Portland cement concrete (PCC), citing its superior durability and chemical stability [28].

A recent study by Albitar et al. reported that fly ash-based GPC demonstrated greater chemical stability and durability under identical curing conditions compared to conventional concrete [29,30]. Similarly, Liew et al. emphasized the substantial environmental advantages of green concrete in construction applications [31]. These benefits include improved workability, higher strength, longer durability, lower permeability, reduced bleeding, enhanced acid resistance, and minimized plastic shrinkage cracking. Further advantages of green concrete include reduced curing times, lower construction and maintenance costs, faster project completion, and extended service life of structures [32]. In a study by Li et al., GPC achieved a compressive strength of 50 MPa at 28 days using ground granulated blast furnace slag (GGBS) as the primary source material. While 28-day compressive strength is a standard benchmark in laboratory testing, results indicate that GPC continues to gain strength up to 90 days. Therefore, it is strongly recommended to assess compressive strength at both 28 and 90 days for a comprehensive evaluation [33].

Although most of GPC's compressive strength develops within the first seven days largely due to accelerated geopolymerization during heat curing a moderate increase is still observed between 28 and 90 days, further supporting its superior mechanical performance [34].

Joseph Davidovits first introduced the concept of geopolymer concrete (GPC) in 1978, utilizing industrial by-products to develop an alternative to conventional concrete [35]. GPC is primarily synthesized using aluminosilicate-rich source materials such as fly ash, ground granulated blast furnace slag (GGBS), and metakaolin. These materials contain high levels of silica and alumina, which are essential for geopolymerization. Alkaline activators—typically sodium hydroxide or potassium hydroxide—are required to dissolve the source materials and initiate the reaction process [19,36].

When these highly concentrated alkaline solutions interact with the aluminosilicate powders, geopolymerization occurs, leading to the development of strength in the concrete [37–41]. The compressive strength of GPC is significantly influenced by the silica and alumina content. For instance, GPC prepared using Class C fly ash and cured in an oven has achieved compressive strengths up to 75 MPa. In contrast, the same GPC mix cured at ambient room temperature (25–30 °C) yields compressive strengths in the range of 47–56.5 MPa. This variation is primarily due to the presence of calcium, which can interfere with the polymerization process and negatively affect the microstructure. Thus, low-calcium formulations are generally preferred for producing high-performance GPC [5,9].

Chen et al. proposed an innovative reinforcement technique in GPC that significantly improves its durability and long-term robustness in construction applications. Saranya et al. demonstrated that GPC reinforced with dolomite and GGBFS exhibited enhanced load-bearing capacity, especially at critical

structural joints such as beam-column intersections. Furthermore, the inclusion of steel fibers in GPC has been shown to enhance ductility and energy absorption properties [7,22]. These improvements, along with the reduced carbon emissions associated with GPC production, make it a suitable material for specialized applications such as subterranean tunnels and gas explosion-prone environments [42]. GPC's performance by incorporating glass and carbon fiber-reinforced polymers, which enhanced both ductility and compressive strength. Compared to conventional source materials, fiber-reinforced geopolymer concrete exhibits superior mechanical properties [43].

While many experimental studies have been conducted on various compositions of GPC, comparative evaluations between geopolymer concrete and ordinary Portland cement (OPC) concrete are still evolving. Based on the literature, several key factors have been identified and are considered essential for the present research: a) To enhance the mechanical and curing properties of GPC by investigating the influence of silica composition. b) To evaluate water absorption characteristics of GPC under varying concentrations of alkaline solutions. c) To analyze the economic index of GPC through the addition of silica-based materials and assess cost-efficiency using regression modeling.

Materials & Methodology

The present research project involves the use of several key materials in the production of geopolymer concrete (GPC). These include coarse aggregates, sand, fly ash, ground granulated blast furnace slag (GGBFS), calcined clay, sodium hydroxide (SH), sodium silicate (SS), water, and a superplasticizer (SP). Additionally, micro silica is incorporated into the mix to enhance performance characteristics. The binder composition of geopolymer concrete is compared with that of ordinary Portland cement (OPC) concrete.

Table 1. Various mix proportion of GPC & OPC concrete.

Kg	Cement	Fine aggregates	Coarse aggregates	GGBFS	Calcined clay	Fly ash	SH	SS	SP	Water
GPC-1	-	658	1222	-	-	400	40	100	6	8
GPC-2	-	658	1222	400	-	-	40	100	6	8
GPC-3	-	655	1216	-	400	-	40	100	6	8
GPC-4	-	658	1222	-	-	400	47	94	6	8
GPC-5	-	658	1222	400	-	-	47	94	6	8
GPC-6	-	658	1222	-	400	-	47	94	6	8
GPC-7	-	658	1222	-	-	400	56	84	6	8
GPC-8	-	655	1216	400	-	-	56	84	6	8
GPC-9	-	655	1216	-	400	-	56	84	6	8
OPC	376	740	1054	-	-	-	-	-	4.2	151

Table 2. Various mix design of GPC and OPC concrete.

Kg	Cement	Micro silica	Fine aggregates	Coarse aggregate	GGBFS	Calcined clay	Fly ash	SH	SS	SP	Water
GPCS-1	-	-	658	1222	360	-	40	40	100	6	8
GPCS-2	-	-	658	1222	320	-	80	40	100	6	8
GPCS-3	-	-	655	1216	200	-	200	40	100	6	8
GPCS-4	-	-	658	1222	360	40	-	40	100	6	8
GPCS-5	-	-	658	1222	320	80	-	40	100	6	8
GPCS-6	-	-	658	1222	200	200	-	40	100	6	8
GPCS-7	-	40	658	1222	320	-	40	40	100	6	8
GPCS-8	-	20	655	1216	340	-	40	40	100	6	8
GPCS-9	-	40	655	1216	320	40	-	40	100	6	8
GPCS-10	-	20	655	1216	340	40	-	40	100	6	8
OPC	376	-	740	1054	-	-	-	-	-	4.2	151

The mix designs for both OPC and GPC were developed in accordance with the guidelines provided by the American Concrete Institute (ACI), specifically ACI 214R-11 and ACI 211.1-02. These standards facilitated the consideration of several critical factors, including the specific gravity, moisture content, and water absorption capacity of the constituent materials. The mix replacement levels and proportions are presented in Tables 1 and 2.

The alkaline solutions were prepared 24 hours prior to casting the concrete, following standard chemical laboratory procedures. The mixing process took approximately five minutes to ensure a homogeneous blend. A superplasticizer was added at 1.0% by mass of the binder. While superplasticizers are commonly used in ordinary Portland cement (OPC) mixes to improve workability, their use in geopolymer concrete (GPC) is optional, as they typically have minimal effect on both workability and strength. All concrete specimens were cured under ambient conditions at a room temperature of 23 ± 5 °C. For each mix, three samples were cast and tested to ensure consistency and reliability of the results. Compressive strength was determined using a digital compression testing machine with a 2000 kN capacity, following the British Standard EN 12390-3:2000, at both 28 and 90 days of curing. The economy index of the concrete was calculated using Equation (1).

$$\text{Economy Index} = \frac{\text{Compressive Strength}}{\text{Total Cost of Production}} \quad (1)$$

Tables 3 and 4 present the production costs per kilogram for ordinary Portland concrete (OPC) and geopolymer concrete (GPC), respectively. As shown in Table 3, the total production cost of OPC is ₹6058.1, with cement contributing a significant share—approximately 49.65% of the total cost. In comparison, Table 4 indicates that the total production cost of GPC is ₹7524.3, with the sodium hydroxide (SH) solution accounting for a major portion—around 26.58% of the total cost.

Life Cycle Cost

A Life Cycle Cost Analysis (LCCA) evaluates the economic, environmental, and performance-related aspects of geopolymer concrete throughout its entire lifecycle—from raw material extraction to production, usage, maintenance, and end-of-life disposal or recycling. The following outline highlights the key components and benefits of LCCA for geopolymer concrete (GPC), with a focus on durability, long-term maintenance, and environmental impact:

Table 3. OPC concrete production cost

Constituent	Rate/Kg	Quantity	Amount	Constituent cost (%)
Coarse Aggregate	1.5	1054	1581	26.09
Sand	1.25	740	925	15.26
Water	1.1	151	166.1	2.74
SP	90	4.2	378	6.23
Cement	8	376	3008	49.65
Total (Kg)			6058.1	100

Table 4. Production cost GPC.

Constituent	Rate/Kg	Quantity	Amount	Constituent cost (%)
Coarse Aggregate	1.5	1222	1833	24.36
Sand	1.25	658	822.5	10.93
Water	1.1	8	8.8	0.11
SP	90	6	540	7.17
Fly Ash	1.8	400	720	9.56
GGBFS	2.85	-	-	-
Calcined Clay	4.8	-	-	-
SH	50	40	2000	26.58
SS	16	100	1600	21.26
Micro Silica	23	-	-	-
Total (kg)			7524.3	100

GPC primarily utilizes industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS), which are more cost-effective and environmentally sustainable compared to the raw materials used in conventional Portland cement. Although initial production costs for GPC can be higher due to less developed supply chains and technologies, these are expected to decline over time with increased adoption and economies of scale. GPC demonstrates superior durability, offering high resistance to fire, sulfates, and acids. Its extended service life surpasses that of ordinary Portland cement (OPC), reducing the frequency of replacements and repairs [8].

The enhanced durability reduces the need for frequent maintenance. GPC is less prone to cracking and environmental degradation. Its resilience in aggressive environments decreases the need for costly repair interventions. GPC production can result in up to 90% lower CO₂ emissions compared to OPC. By using industrial waste materials, GPC diverts waste from landfills and minimizes the environmental impact of raw material extraction. The manufacturing process is less energy-intensive than that of OPC. GPC offers better recyclability, supporting the principles of a circular economy [44].

Though GPC may require a higher initial investment, long-term benefits—such as reduced maintenance, increased durability, and environmental compliance—often outweigh the upfront costs. When considering the full lifecycle—including production, maintenance, and environmental costs—GPC often proves more cost-effective than OPC. The economic viability of GPC varies depending on project scale, location, and implementation logistics: Higher per-unit cost due to small-scale production and limited bulk procurement. Logistics and setup costs may be higher, especially in regions lacking established supply chains. Significant cost savings over time due to lower maintenance and repair needs. Upfront investment remains a barrier in the absence of long-term financial projections or supportive economic policies [45].

Proximity to power plants or steel industries can reduce transportation costs for fly ash or GGBFS. Skilled labor for GPC production may command higher wages, although local sourcing can reduce transportation expenses. Rising demand in the construction sector can drive up material costs due to competition and limited availability. GPC aligns well with sustainability regulations, making it an attractive option for environmentally conscious construction practices [46].

RESULTS & DISCUSSION

The economy index of Ordinary Portland Cement (OPC) and Geopolymer Concrete (GPC) with varying compositions is compared based on their compressive strength and total production cost. This index serves as a critical metric to evaluate the cost-effectiveness of each concrete type in structural applications. Curing plays a vital role in the development of strength and durability, and it is also a significant factor in water absorption testing, which is essential for assessing the long-term performance of concrete in structural environments.

Compressive Strength

Figures 2 and 3 illustrate the measured compressive strengths of Geopolymer Concrete (GPC) and Ordinary Portland Cement (OPC). As shown in Figure 2, sample GPC-2 achieved the highest compressive strength among all tested mixes. Similarly, GPC-5 outperformed other geopolymer samples, such as GPC-1 and GPC-8, in terms of compressive strength. Overall, GPC-2 demonstrated the maximum compressive strength when compared to both other geopolymer mixes and the OPC counterpart. In Figure 3, the addition of silica is evident in the performance of GPC-7, which exhibited the highest compressive strength among the silica-modified mixes.

The residual compressive strength refers to the maximum stress that a material can withstand after sustaining damage under load. For geopolymer concrete, this property is heavily influenced by its ability to resist crack propagation. However, under elevated temperatures, the residual compressive strength of GPC tends to decrease. Heat exposure is a key factor affecting the shape, color, and surface characteristics of concrete. Therefore, residual compressive strength is a crucial indicator of the thermal durability and structural resilience of geopolymer concrete.

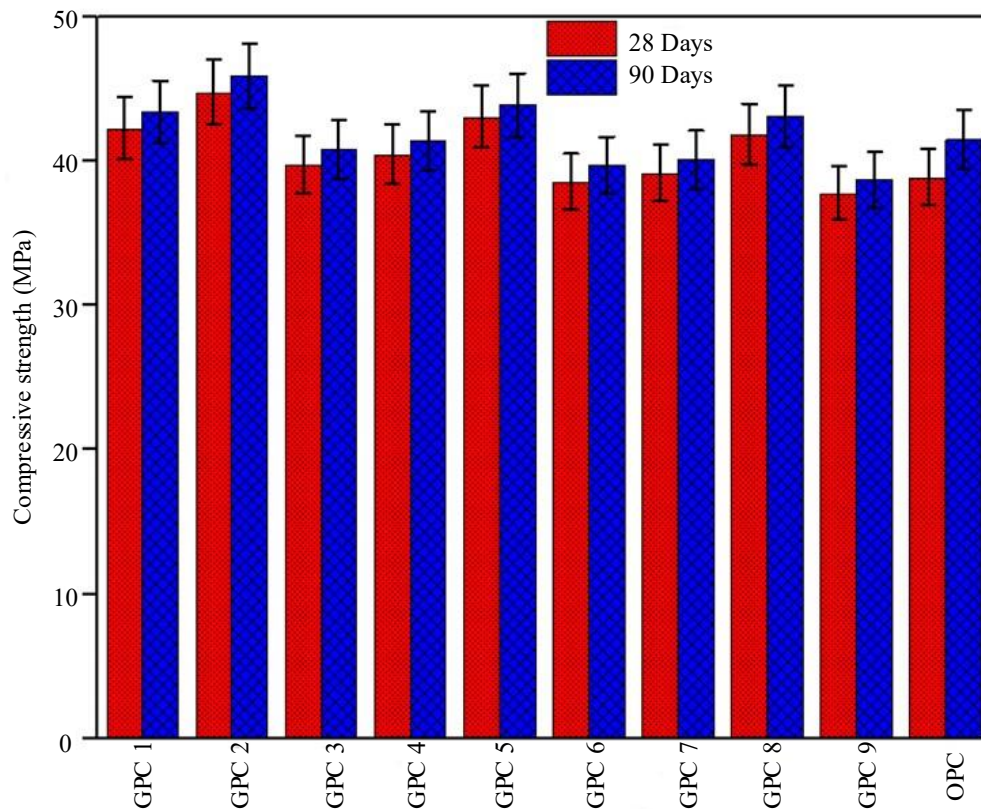


Figure 2. Compressive strength of GPC and OPC concrete.

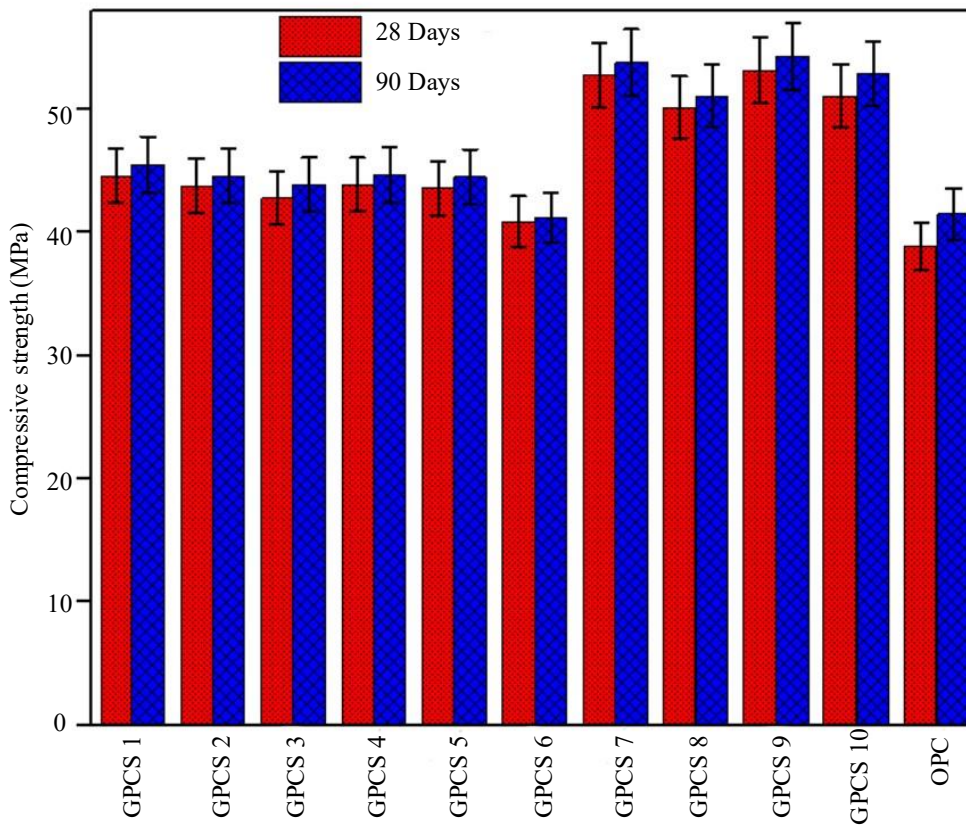


Figure 3. Compressive strength of GPC with silica and OPC concrete.

The bar chart presents the compressive strength results (in MPa) for various Geopolymer Concrete (GPC) mixes (GPC 1–9) and Ordinary Portland Cement (OPC), measured at two curing intervals: 28 days (in red) and 90 days (in blue). The overall trend highlights the superior performance of several GPC formulations over OPC, particularly with extended curing time. GPC-2 exhibited the highest compressive strength among all samples, both at 28 days and 90 days. This suggests an optimal combination of binder composition and activator concentration in GPC-2 that promotes enhanced geopolymerization. GPC-5 also demonstrated excellent performance, ranking as one of the top-performing mixes. Its strength surpasses OPC significantly, suggesting that its material composition—potentially rich in silica and activated by suitable alkali solutions—contributed to robust matrix development. GPC-1, GPC-4, and GPC-7 showed comparable strengths, consistently outperforming OPC, particularly at 90 days, highlighting the extended gain in strength due to ongoing geopolymerization. GPC-6, GPC-8, and GPC-9, while slightly trailing in early strength, showed reasonable improvements at 90 days. This delayed strength gain is typical of geopolymer systems, especially under ambient curing, where the reaction kinetics are slower. GPC-3 had the lowest strength among the GPC series but still remained competitive with OPC, especially by 90 days [47].

OPC reached a maximum strength of just above 41 MPa at 90 days. However, six GPC mixes (GPC-1, GPC-2, GPC-4, GPC-5, GPC-7, and GPC-8) outperformed OPC in both curing durations. This illustrates the viability of GPC as a high-performance alternative to traditional Portland cement, particularly when considering its reduced environmental footprint. A clear increase in strength from 28 to 90 days is observed in all mixes, highlighting the continuous development of the geopolymer matrix over time. The increase in compressive strength over time is more significant for GPC than for OPC. This is due to the nature of geopolymerization, which is a gradual process influenced by the availability of reactive silica and alumina and their interaction with the alkali activators. Notably, GPC-2 and GPC-5 show the most significant strength gain, confirming the effectiveness of their mix design and curing protocol. Based on mix references, samples such as GPC-7, which are enhanced with micro silica, showed improved compressive strength compared to others without silica enhancement. The presence of additional silica likely contributed to a denser matrix and improved pozzolanic activity, thereby increasing strength [48]. The error bars show acceptable variability across all samples, indicating good repeatability and consistency of the experimental procedure. Minimal deviations suggest that the compressive strength values are reliable and indicative of actual material behavior [49].

Economy Index

Based on the results, conventional Portland concrete exhibits an economy index of 5.87. All geopolymer concrete mixes demonstrated a lower economy index compared to traditional Portland concrete. This is primarily attributed to the higher compressive strengths achieved by geopolymer concrete, particularly those incorporating ground granulated blast furnace slag (GGBFS). The key cost distinction between ordinary and geopolymer concrete lies in the expense of cement versus source materials. While cement significantly drives up the cost of Portland concrete, the source materials used in geopolymer concrete such as fly ash and GGBFS are industrial by-products derived from steel and other manufacturing sectors. These materials are generally more affordable and sustainable, contributing to the overall cost-efficiency and performance of geopolymer concrete.

The comparative analysis of production cost, compressive strength, and economy index for Ordinary Portland Concrete (OPC) and various Geopolymer Concrete (GPC) mixes provides valuable insights into their cost-effectiveness and structural performance. OPC exhibits a production cost of Rs. 7.10/m³ and a compressive strength of 41.5 MPa, resulting in the highest economy index of 5.87 among all mixes. This high economy index indicates a favourable balance between cost and strength, making OPC traditionally economical in conventional construction scenarios. The economy indices of GPCs range from 1.51 to 4.56, indicating a broader performance variation based on material composition and mix design. GPC-1 (1.51) and GPC-2 (1.70) show the lowest economy indices, despite having relatively moderate production costs (Rs. 8.83 and Rs. 9.32 respectively). This is due to their low compressive strengths (13.4 MPa and 15.9 MPa), making them less efficient for structural applications where strength is critical. Such mixes may be more suitable for non-load-bearing applications or where cost and environmental factors outweigh strength considerations.

GPC-3 to GPC-9 exhibit higher compressive strengths, ranging between 38.7 MPa and 43.9 MPa, bringing them closer to or exceeding OPC's performance. Among these, GPC-5 shows the highest compressive strength (43.9 MPa) and an economy index of 4.56, indicating its suitability for structural use with a relatively high performance-to-cost ratio. GPC-4 and GPC-8 also perform well with economy indices of 4.53 and 4.33, respectively, suggesting that optimized GPC formulations can rival OPC in both strength and cost-effectiveness. The variability in economy indices across GPCs can be attributed to differences in source materials (fly ash, GGBFS, metakaolin), alkali activators, and curing conditions. The use of GGBFS, in particular, contributes significantly to increased strength, as seen in GPC-5 and GPC-4.

While OPC maintains the highest economy index overall, certain GPC mixes (notably GPC-4, GPC-5, and GPC-8) approach or exceed its strength with a reasonable cost, making them viable and sustainable alternatives [50]. GPCs offer added environmental advantages, such as reduced carbon footprint and utilization of industrial by-products, which aren't captured directly in the economy index but are crucial for sustainable development. Optimization of GPC mix design is essential to achieving the best balance between cost and performance. With further development and wider adoption, production costs of GPCs may decrease, further improving their economic viability [51].

This analysis compares Ordinary Portland Concrete (OPC) with ten geopolymer concrete samples enhanced with silica (GPCS-1 to GPCS-10). The goal is to evaluate the economic and structural performance of each concrete mix using three key parameters: production cost per cubic meter, compressive strength (MPa), and economy index (compressive strength divided by cost). OPC Production Cost is ₹7.10/m³, Compressive Strength is 41.5 Mpa, and Economy Index is 5.84. The OPC mix serves as a benchmark in this comparison. With a moderate cost and high strength, OPC maintains the highest economy index, making it currently the most cost-effective option on a compressive strength per cost basis. Most GPCS mixes demonstrate competitive or superior performance in terms of strength, though with slightly higher production costs than OPC.

GPCS-10 has Strength - 52.9 Mpa, Cost: ₹9.88 and Economy Index 5.35. Offers excellent strength with a strong economy index, close to OPC. Suggests very good cost-effectiveness for high-strength applications. GPCS-9 Strength: 54.3 Mpa, Cost: ₹10.36, Economy Index: 5.24. Highest strength among all samples, showing suitability for high-performance structures. High cost slightly reduces its economy index but still remains efficient. These mixes offer compressive strengths comparable to OPC, but with slightly lower economy indices due to increased production costs. GPCS-1 to GPCS-5 (Strengths between 43.9 MPa and 45.5 MPa): Economy indices range from 4.68 to 4.90. Good performance overall, but the cost per MPa is slightly higher than OPC. Can still be considered in applications where environmental or durability advantages outweigh initial cost differences.

Many GPCS mixes, particularly GPCS-7 to GPCS-10, offer significantly higher compressive strength than OPC, suggesting suitability for high-strength or performance-demanding applications. While OPC has the highest economy index (5.84), GPCS-10 (5.35) and GPCS-7 to GPCS-9 (5.24–5.26) are very competitive and could become more economical as production scales and costs decrease. The higher production cost of GPCs is largely attributed to the use of activators and micro-silica, but this is compensated by improved mechanical properties [52]. Although not reflected in the economy index, GPCS mixes offer significant environmental advantages—lower carbon emissions, industrial waste utilization, and better chemical resistance. GPCS-7 to GPCS-10 stand out as the best-performing mixes, offering superior strength and economy indices close to or even rivaling OPC. With ongoing advancements in material availability and production efficiency, these silica-based GPCs show great promise for replacing OPC in sustainable and performance-critical construction [53].

Regression Models

Figures 4 and 5 illustrate the regression analysis results for OPC and GPC based on their economy indices. The coefficient of determination (R^2) for OPC is 81.7%, while for GPC it is 17.6%, both evaluated at 28 days of curing in relation to compressive strength. This suggests that for OPC, there is

a strong correlation between compressive strength and economy index, indicating a well-fitting model with high predictive accuracy at the 95% confidence level. In contrast, the lower R^2 value for GPC implies a weaker relationship, suggesting that additional factors may influence the economy index beyond compressive strength alone. Despite this, the regression models are appropriately fitted within their respective datasets.

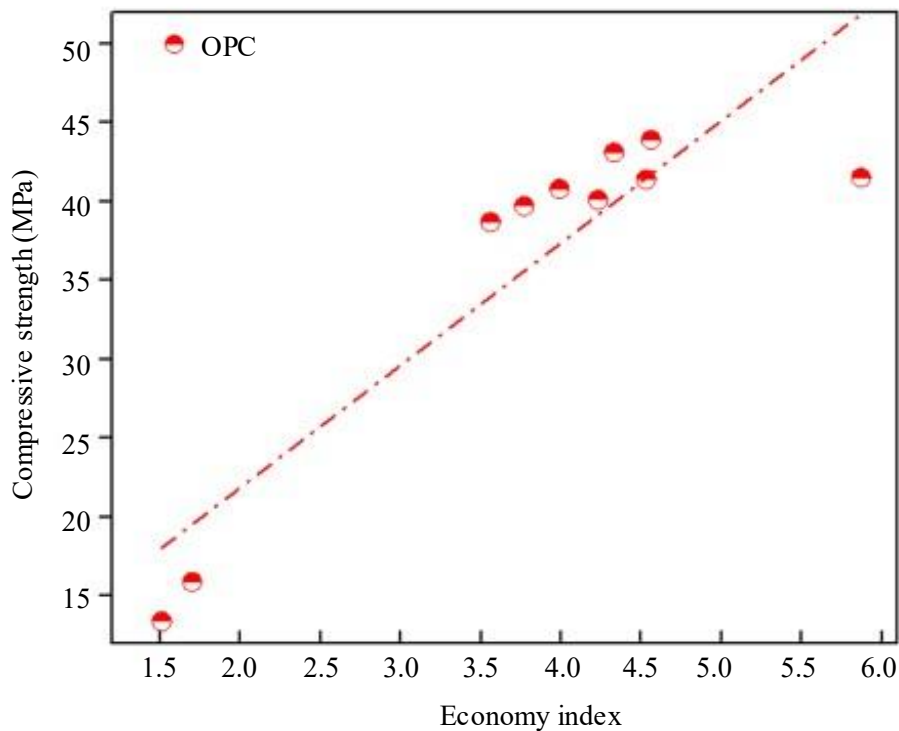


Figure 4. OPC concrete regression model.

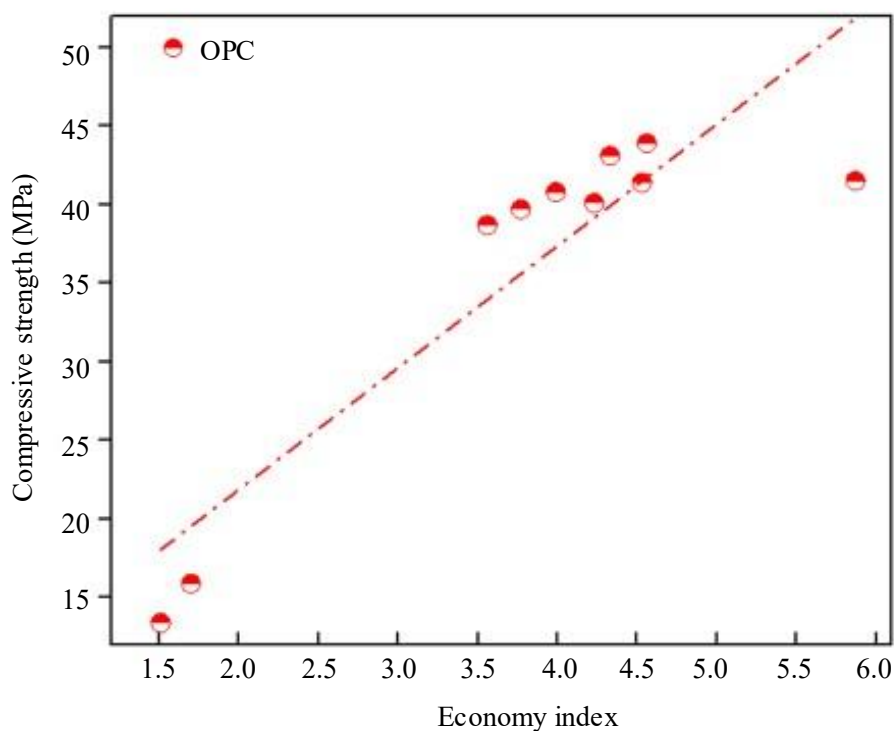


Figure 5. GPC regression model.

Water Absorption

In accordance with ASTM C642-06, specimens with dimensions of 100 mm in diameter and 75 mm in height were prepared for testing, as illustrated in Figures 6 and 7. After 28 days of curing, the specimens were weighed and then placed in an oven at a temperature of 100 ± 10 °C for a minimum of 24 hours to determine their oven-dry mass (W_d). The specimens were then allowed to cool in a desiccator [54]. Only those specimens showing a weight variation of less than 0.5% between successive measurements were considered valid. Subsequently, the specimens were submerged in water for at least 48 hours, after which the saturated mass after immersion (W_s) was recorded. Again, only specimens with less than 0.5% weight variation between final and initial readings were accepted for analysis. The water absorption percentage results are represented in terms of the following equation (2) is, Where, (W_i) is denoted as initial weight. The water absorption test readings are presented in figure 6 & 7.

$$\text{Water Absorption test (\%)} = \left[\frac{W_s - W_d}{W_d} \right] \times 100 \quad (2)$$

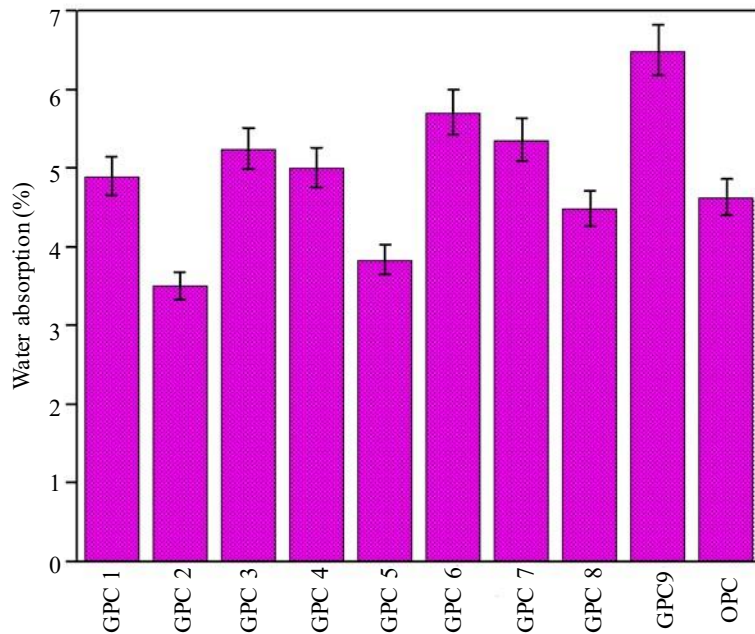


Figure 6. Graph of water absorption percentage in GPC and OPC concrete.

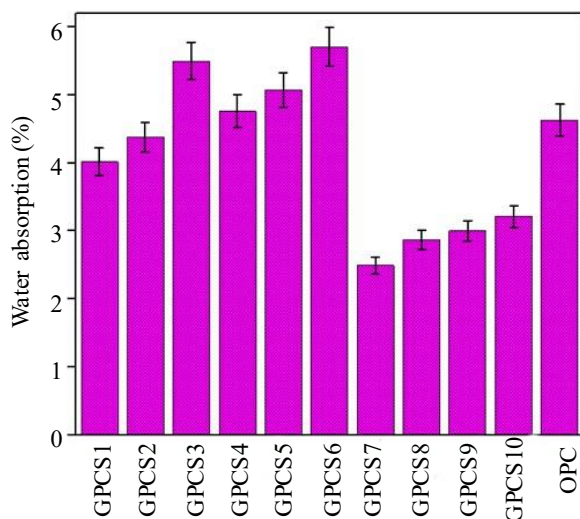


Figure 7. Graph of different mix designs water absorption.

Figure 6 illustrates the variation in water absorption values across different geopolymer concrete (GPC) compositions. According to Nagaratnam et al., immersion absorption reflects the amount of water a material absorbs when submerged for a specified duration. Among the tested mixes, GPC-2 recorded the lowest absorption value at 3.5%, indicating better resistance to water ingress. When silica was incorporated into the GPC mix, the water absorption further decreased, with a minimum value of 2.49%, as shown in Figure 7. These results align with findings from previous studies, which suggest that a lower water-to-binder ratio in GPC leads to reduced absorption. In contrast, ordinary Portland cement (OPC) concrete exhibited significantly higher absorption values, reaching 6.5% and 5.71%, respectively, highlighting the superior impermeability characteristics of geopolymer concrete [4].

A global shortfall of approximately 1.7 billion tons exists when considering the amount of slag cement required to fully replace Ordinary Portland Cement (OPC) with geopolymer concrete (GPC). Based on data from the United States, which has the most limited availability of slag cement, only 2.4% of annual OPC production could be substituted with slag-based GPC. Globally, the available surplus of slag cement allows for a maximum replacement of 6.5% of annual OPC concrete production. Similarly, metakaolin, another common binder in GPC, is not produced in sufficient quantities to replace OPC on a global scale. In the most restricted market, such as China, less than 1% of current OPC concrete production could be substituted with metakaolin-based GPC. On a global scale, only 1.4% of concrete production could be replaced due to the limited supply of metakaolin [55].

Sodium hydroxide, a key alkaline activator in GPC, presents another constraint. It is not only the most expensive raw material used in GPC production, but also has limited availability and few alternatives. As a result, GPC production constrained by sodium hydroxide availability could only replace up to 2% of global OPC concrete production. Despite these limitations, geopolymer concrete is increasingly adopted in the construction industry due to its significant advantages over OPC. These include higher early strength, enhanced durability, reduced permeability, and lower shrinkage cracking. Researchers have successfully used various source materials—particularly fly ash and lightweight industrial by-products—to enhance performance while reducing environmental impact [56].

Laskar and Talukdar conducted extensive studies on GPC using ultrafine Ground Granulated Blast Furnace Slag (GGBFS) and fly ash as binding agents. Fly ash content in binders ranged from 0% to 50%, while alkali activators (NaOH) were used at concentrations between 8 M and 14 M. Results showed that GPC developed rapid early strength, achieving up to 60% of its ultimate strength within 24 hours. However, when fly ash content exceeded 40%, compressive strength began to decline, despite improved workability. Similarly, Deb et al. (2014) investigated Class F fly ash as a primary binder and used a combination of sodium hydroxide and sodium silicate to produce the alkaline solution. The ratio of sodium hydroxide to sodium silicate was increased from 1.5 to 2.5, and slag content varied between 0% and 20%. Samples cured at ambient temperature (with approximately 75% relative humidity) exhibited increased compressive strength with higher slag content, but excessive alkaline activator ratios led to strength reductions [49].

Top and Vapur reported a compressive strength of 50 MPa at 28 days for GPC prepared with fly ash. Lee et al. used a mix of 70% fly ash and GGBFS with varying NaOH concentrations (2 M to 6 M), keeping the GPC sand gravel ratio at 1:2.5:2.4. Cylindrical samples were cured both indoors and outdoors, and compressive strength was measured at 14, 28, 56, 90, 180, and 270 days. Outdoor curing resulted in shrinkage and strength reduction, whereas indoor samples retained and continued to gain strength over time, emphasizing the importance of proper curing.

One of the most notable applications of GPC is at the Brisbane West Wellcamp Airport in Australia. Glasby et al. reported the use of approximately 40,000 m³ of fly ash-based GPC, provided by Wagner, for various parts of the airport including the runway (northern end), turning zones, taxiway (west), and hangars (east). The airport has been fully operational and in use by QantasLink for commercial flights since November 2014, demonstrating the feasibility and performance of GPC in large-scale infrastructure projects [45].

Chloride Penetration Resistance

The chloride penetration resistance is calculated by Rapid Chloride Permeability Test (RCPT standard ASTM C1202), a voltage potential is applied across the samples and the amount of charge (Q) passed through test samples was calculated in coulombs using equation (3), which was derived using the trapezoidal law and data collected every 30 minutes.

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \dots + 2I_{330} + I_{360}) \quad (3)$$

Where I is the current in Amps at each 30 minutes interval and 900 is the conversion factor for 30 minutes *60 seconds * 0.5 for trapezoidal rule.

The Table 5 and figure 8 shows the chloride ion permeability of 9 GPC mixes and OPC, measured by average current in Coulombs. Lower values mean better resistance to chloride ingress, as GPC-2 has the lowest coulombs meaning highest durability for all the mixes. In contrast, OPC was the highest, thus, poorest chloride resistance. GPC-7 also performed well with a considerably lower permeability than OPC. Most GPC mixes what has better performance compared to OPC foreshadowing the clearly superior durability of geopolymer concretes. This indicates optimized GPC formulations have low permeability and are effective in resisting chloride and therefore cause of chloride induced corrosion making them feasible in an aggressive environment.

Table 5. Chloride penetration resistance of OPC and GPC.

Mix id	Average current (coulombs)	Chloride penetration
GPC-1	1430	low
GPC-2	900	Very low
GPC-3	1780	low
GPC-4	1890	low
GPC-5	1960	low
GPC-6	2560	Moderate
GPC-7	1545	low
GPC-8	2160	Moderate
GPC-9	1560	low
OPC	2760	Moderate

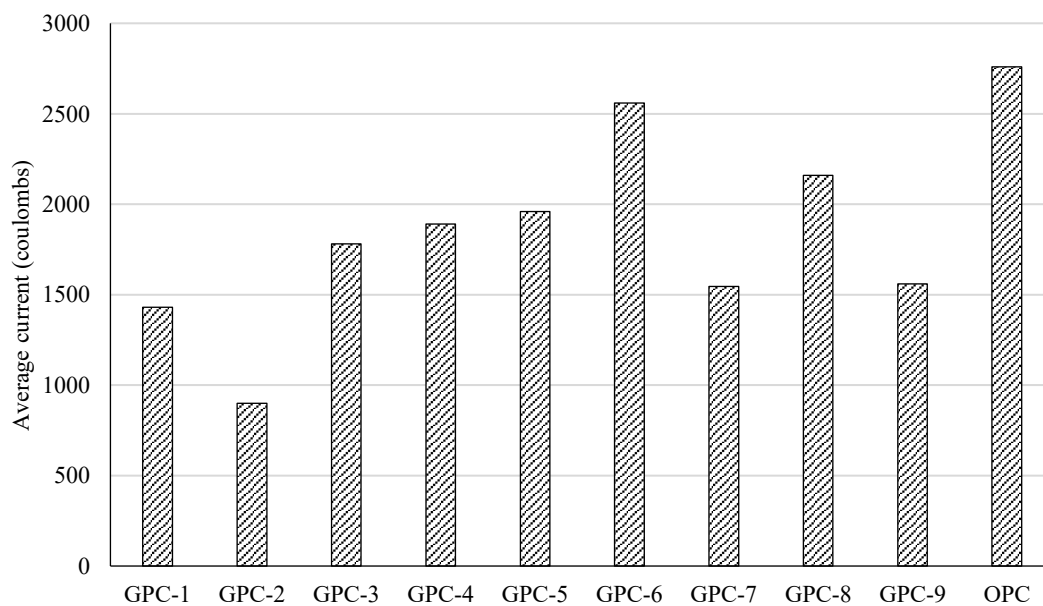


Figure 8. Chloride penetration resistance of OPC and GPC.

Table 6. Chloride Penetration resistance of OPC and GPC with Silica.

Mix id	Average current (coulombs)	Chloride penetration
GPCS-1	1230	Low
GPCS-2	1350	Low
GPCS-3	1310	Low
GPCS-4	1540	Low
GPCS-5	2330	Moderate
GPCS-6	2260	Moderate
GPCS-7	870	Very low
GPCS-8	1360	Low
GPCS-9	1960	Low
GPCS-10	1345	Low
OPC	2420	Moderate

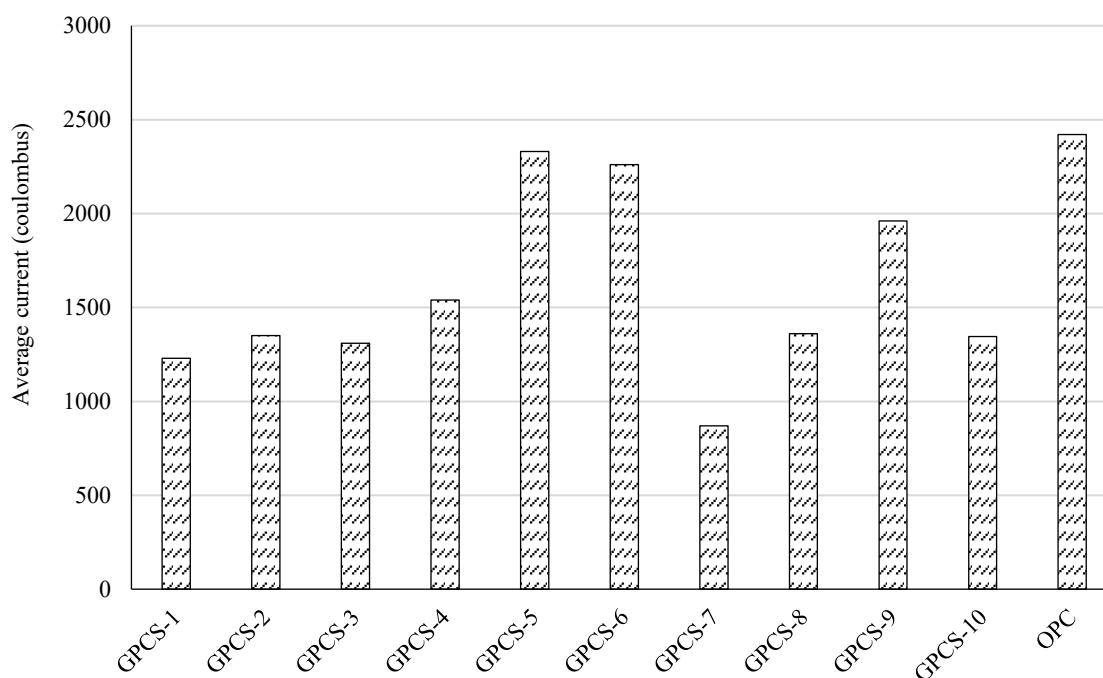
**Figure 9.** Chloride penetration resistance of OPC and GPC with silica.

Table 6 and Figure 9 demonstrates the chloride penetration resistance of the concrete mixes (GPCS-1 to GPCS-10, and the OPC) using the RCPT. Lower average current (in coulombs) means better resistance to chloride ingress. GPCS-2 and GPCS-7 show the lowest values suggesting better durability. However, GPCS-5, GPCS-6 and OPC are both higher, suggesting the higher permeability than the other mixes. As GPC mixes performed better than the OPC, highlighting that the GPCS mix will have enhanced chloride resistance. The data also shows that there is potential for geopolymer formulations to enhance durability over time in aggressive environments, especially if uses supplementary materials such as GGBFS and fly ash.

Compressive Strength under Sulphate Attack

Sulphate attack testing incorporated exposing specimens to a 10% sodium sulphate (Na_2SO_4) solution. For the sulphate solution, how the compressive strength changes for OPC, GPC and GPCS specimens under the various curing conditions.

Table 7. Compressive strength of OPC and GPC under sulphate attack.

Mix id	Compressive strength		
	28days	56days	90days
GPC-1	36.6	38.2	39.4
GPC-2	44.2	48	52.3
GPC-3	42.5	39.2	42.9
GPC-4	37.2	40.1	44.2
GPC-5	38.3	39.4	42.1
GPC-6	39.2	44.2	46.5
GPC-7	37.5	40.4	43.5
GPC-8	39.7	37.7	40.2
GPC-9	40.7	42.4	36.6
OPC	36.1	39	40.2

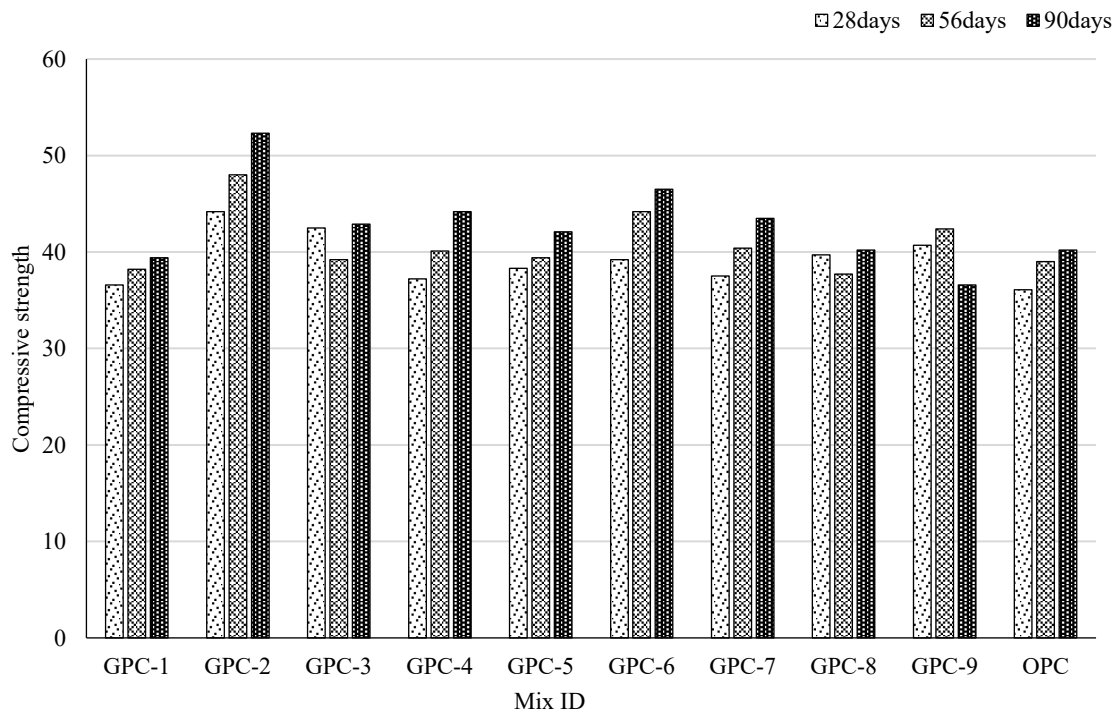
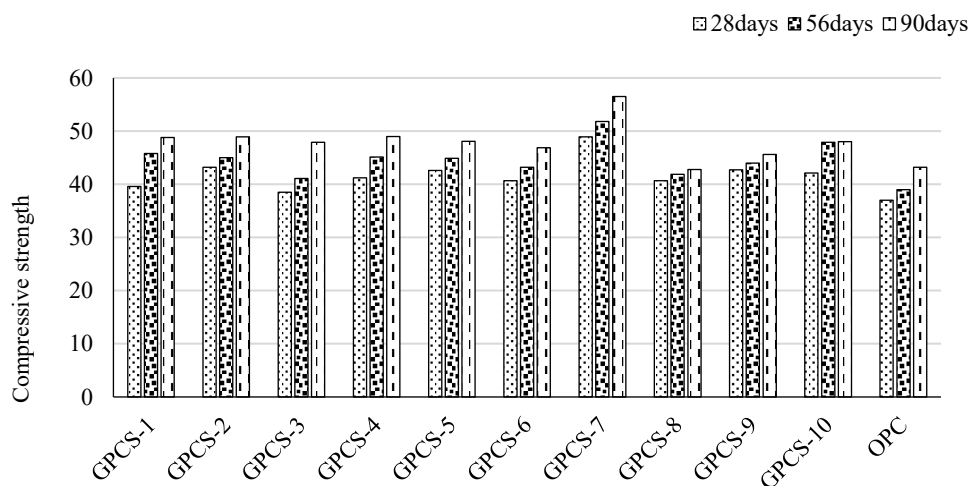


Figure 10. Compressive strength of OPC and GPC under sulphate attack.

Table 7 presents the CS of various GPC mixes as well as OPC after 28, 56 and 90 days of exposure to sulphate. Just like the other curing conditions, and as has been observed previously, the strength generally increases with age for all mixes. Figure 10 compares the compressive strength development of the different concrete mixes from GPC-1 to GPC-9 OPC at 28, 56 and 90 days. The significant majority of GPC mixes have higher compressive strength than the OPC at 90 days which indicates their capacity for long term performance gain over OPC. GPC-2 continued to have the greatest strength of all the mixes and experienced appreciable gains between 28 days to 90 days. OPC exhibited minor strength gain, but still less than the less than the best GPC mixes. It is evidenced from this data that, with good design, GPC mixes can develop the same strength as OPC and potentially exceed the performance of the strength of OPC, with expected higher performance development at longer curing periods.

Table 8. Compressive strength of OPC and GPCS under sulphate attack.

Mix id	Compressive strength		
	28days	56days	90days
GPCS-1	39.6	45.8	48.8
GPCS-2	43.2	45	48.9
GPCS-3	38.5	41.1	47.9
GPCS-4	41.2	45.1	49
GPCS-5	42.6	44.9	48.1
GPCS-6	40.7	43.2	46.9
GPCS-7	48.9	51.8	56.5
GPCS-8	40.7	41.9	42.8
GPCS-9	42.7	44	45.6
GPCS-10	42.1	47.9	48
OPC	37	39	43.2

**Figure 11.** Compressive strength of OPC and GPCS under sulphate attack.

In the same way, the GPC with silica mixes and OPC compressive strength chart after 28, 56, and 90 days of soaking in sulphate, are depicted in table 8. The identified GPCS-1 to GPCS-10 and OPC compression strength values are compared in figure 11 at 28, 56, and 90 days. All GPCS mixes display a larger compressive strength over time, with the 90 days values always higher than at both 28 or 56 days. GPCS-7 provides the highest compressive strengths, still surpassing OPC at all three points in time. The analysis has revealed the GPCS mixes provide better overall compressive strength than OPC, early and long term, as the increasing silica in GPC was shown to be a positive modification for GPC.

Analysis of Carbonation Depth

The carbonation depth is the distance CO_2 from the atmosphere has travelled into the concrete structure to the point it is in the process of changing the pH. The depth of carbonation was measured by splitting the specimens and exposing them to phenolphthalein solution to measure the carbonation effects on the pH change in concrete. Carbonation reduces the pH of concrete. When the pH is less than a certain depth (~ 9), the steel reinforcement has the potential to start corroding as the passive protective layer surrounding the steel will deteriorate. The risk of steel corrosion will increase as that carbonation depth increases and the durability of the concrete decreases. The Figures 12 and 13 below show the average carbonation depth analysis of OPC, GPC and OPC, GPC with silica (respectively). For GPC mixes in figure 12, the average carbonation depth range was least for GPC-2 with 2.2 mm, and the OPC concrete had the most carbonation depth with 6.6 mm.

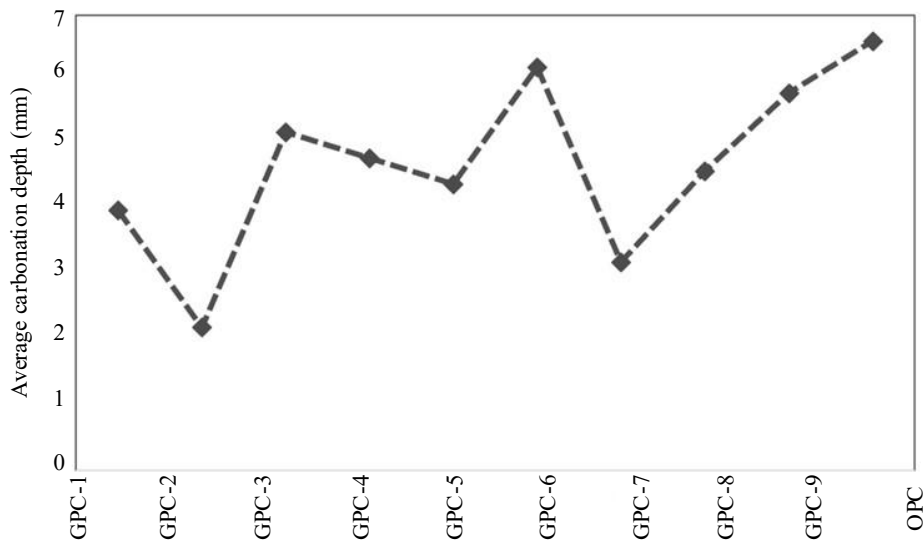


Figure 12. Average carbonation depth of OPC and GPC.

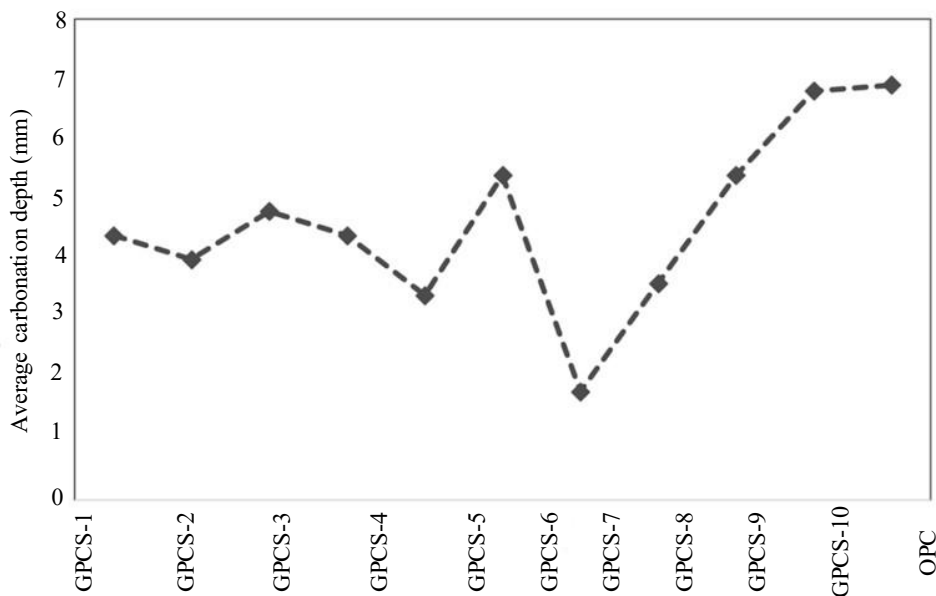


Figure 13. Average carbonation depth of OPC and GPCS.

Figure 13 shows the average carbonation depth for GPCS-1 to GPCS-10 and OPC. Graphs 12 and 13 show there are significant carbonation depth variances among mixes with silica material. OPC had the highest average carbonation depth, around 6.9 mm. However, several GPCS blends were within a range of average depth with GPCS-7 developing the least average carbonation depth, when comparing carbonation resistance among other mixes. This indicates the blending of GGPFs likely has an effect on the resistance to carbonation. However, the level of effect depends on the individual mix composition and the percentage of slag in each GPCS blend. Undoubtedly, GPCS acceleration/resistance to carbonation compared to normal concrete with significant carbon uptake demonstrated the variable performance during the evaluation of the GPCS blends, relating to optimized mixes for improved carbonation resistance.

DISCUSSION

Despite the numerous benefits of geopolymer concrete (GPC)—including its excellent strength-to-weight ratio, high resistance to aggressive environments, and potential for reduced environmental impact several challenges hinder its widespread adoption in the construction industry. One of the

primary challenges is the high initial cost associated with raw materials and the specialized expertise required for GPC production. These factors make it difficult for small-scale construction projects to adopt the technology. Furthermore, the lack of standardized codes and specifications has limited its acceptance and integration into mainstream construction practices [57].

Although experimental research has proven GPC's outstanding mechanical and durability properties, its long-term performance under real-world conditions remains inadequately understood. As production scales up, inconsistencies in material quality and performance have emerged, which poses significant barriers to large-scale industrial application. To unlock the full potential of geopolymer concrete, further research and innovation are essential. Key areas requiring attention included A holistic analysis of GPC's environmental and economic impacts is crucial for increasing awareness and promoting adoption. Studies suggest that innovative strategies could significantly reduce production costs without compromising performance or sustainability [58].

While GPC has demonstrated rapid early strength gain, particularly with slag- or fly ash-based mixtures, long-term studies are lacking, especially for mixes using non-traditional precursors. Accelerated testing methods should be explored to evaluate durability and reliability over time. GPC is a sustainable and innovative substitute for Ordinary Portland Cement (OPC) concrete. Its use offers numerous advantages, including reduced CO₂ emissions, greater durability, and the utilization of industrial by-products such as fly ash and GGBFS. To facilitate its widespread adoption, supportive policies and strategic initiatives must be introduced. Provide tax incentives to construction firms and developers using GPC to reduce initial investment costs [59]. Offer subsidies for the procurement of industrial by-products such as fly ash and GGBFS to reduce production costs. Integrate GPC into national and regional construction codes and standards to promote its formal use in projects. Encourage the use of low-carbon materials like GPC by imposing stricter regulations on OPC production emissions. Allocate public funding to R&D aimed at improving GPC formulations, reducing costs, and enhancing long-term durability. Promote collaborations between government, academia, and industry for field trials and pilot projects. Introduce educational and training initiatives to equip professionals with the skills needed for GPC production and application. Educate stakeholders, including contractors, developers, and consumers, about GPC's environmental and structural benefits. Mandate or incentivize the use of GPC in government-funded infrastructure and construction projects. Implement government-supported pilot projects to showcase the performance and feasibility of GPC in real-life scenarios [60].

Establish ISO-level certifications and performance benchmarks to validate the quality and safety of GPC products. Engage independent agencies for product verification, ensuring credibility and boosting market confidence. Introduce carbon taxes on OPC production to create a level playing field and increase GPC's market competitiveness. Support industries that supply fly ash, slag, and other waste materials with incentives to encourage circular economy practices [61]. Collaborate with international regulatory bodies to standardize GPC performance criteria across borders. Organize global forums, conferences, and workshops for the dissemination of best practices, case studies, and research outcomes. By addressing these technical, regulatory, and economic challenges, geopolymer concrete can become a mainstream, eco-friendly alternative to OPC, promoting sustainability, reducing carbon footprints, and enabling innovative construction practices for future infrastructure [62].

The present study focuses on developing a chemically predictive model for comparing the performance of geopolymer and ordinary concrete, it does not incorporate quantitative kinetic modeling or Arrhenius-based activation energy analysis. This omission was intentional, as our primary objective was to correlate compositional variables with engineering properties such as compressive strength and durability, which are directly relevant for field applications and material optimization. However, we acknowledge that geopolymerization is a complex, temperature- and alkali-sensitive process, and deeper mechanistic insights could be achieved through isothermal calorimetry or kinetic model-fitting approaches. Future research will aim to incorporate these methods to quantify reaction kinetics and activation energies, which would complement our current macroscopic modeling by elucidating the underlying reaction pathways and rate-limiting steps more rigorously.

To improve the predictability of compressive strength in geopolymer concrete (GPC), future research will incorporate multivariate regression and machine learning techniques such as multiple linear regression (MLR) and artificial neural networks (ANN). These methods are expected to model complex interactions among key mix constituents—such as sodium hydroxide concentration, sodium silicate ratio, GGBFS proportion, and the liquid-to-binder ratio—more accurately than univariate economic indicators. Such data-driven approaches will enhance the robustness and practical applicability of chemically predictive models in the context of geopolymer mix design and optimization.

This study provides insights into the mechanical and economic performance of geopolymer concrete, it does not explicitly account for real-world constraints such as regional availability of precursors like GGBFS, metakaolin, and alkaline activators. These limitations may significantly impact the scalability and economic feasibility of GPC in various geographic regions. To enhance practical applicability, future research should incorporate regional supply chain models and location-specific LCA frameworks. Doing so will provide more comprehensive and realistic assessments, helping stakeholders evaluate the feasibility of GPC deployment at scale.

CONCLUSION

The evaluation of Ordinary Portland Cement (OPC) concrete and geopolymer concrete (GPC), utilizing sodium hydroxide and sodium silicate as activators, has revealed notable differences in terms of production cost and economic index. This research facilitated a comprehensive assessment of the economic viability of manufacturing sustainable geopolymer concrete in comparison to conventional OPC concrete. A regression model was developed to forecast the relationship between compressive strength and the economy index, enabling better understanding of the cost-performance dynamics. Based on these findings, it is strongly recommended that standard operating procedures and protocols be consistently followed when evaluating the production cost and economic impact of geopolymer concrete. The study also analyzed water absorption and economy index outcomes for different GPC compositions. It was observed that geopolymer concrete with a higher activator-to-binder ratio exhibited the lowest water absorption, indicating superior durability. However, the variation in absorption across different GPC mixes was relatively minimal. In contrast, OPC concrete demonstrated significantly higher absorption levels than GPC-2 and GPCS-7, which also achieved higher compressive strengths. Notably, the inclusion of micro-silica or ultra-fine silica materials in GPC formulations, as seen in GPCS-7, resulted in improved residual compressive strength. This suggests that fine additives can play a critical role in enhancing performance characteristics. From an economic standpoint, substituting OPC with geopolymer concrete could lead to cost savings ranging from 31.13% to 43.74%, depending on the mix design and material availability. These cost benefits, combined with improved performance and sustainability, underscore the viability of GPC as a replacement for OPC.

Geopolymer concrete is already being considered for a wide range of civil engineering applications. Apart from its use in conventional structural elements such as beams, columns, and slabs, GPC can also be effectively employed in the construction of railway sleepers, bricks, barriers, pavements, retaining walls, water tanks, boat ramps, precast bridge decks, and even in soil stabilization works. These applications demonstrate the versatility and potential of GPC in both structural and infrastructure development sectors.

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