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Influence of Ambient and Oven Curing on Strength Development of Fly Ash–Based Geopolymer Concrete and OPC Concrete

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Abstract
The cement industry remains one of the largest contributors to global CO_2 emissions, underscoring an urgent demand for sustainable alternatives in construction materials. Geopolymer concrete has emerged as a promising eco-friendly replacement for ordinary Portland cement (OPC), owing to its capacity to utilize industrial by-products such as fly ash and its potential to substantially reduce carbon emissions. Among various supplementary materials, Class F fly ash presents a viable pathway for sustainable development through complete cement substitution. Although extensive research has investigated the mechanical performance of geopolymer concrete, the underlying strength development mechanisms remain critical for determining its suitability across diverse construction applications. Existing studies indicate notable sensitivities related to compressive strength development and curing conditions, which must be addressed to enable wider adoption in structural practice. In present study, M25, M30, and M40 grade geopolymer concrete mixes were produced using 100% Class F fly ash as a binder. Sodium hydroxide and sodium silicate solutions were employed as alkaline activators at a concentration of 13M in the fresh mix. The experimental programme was designed to assess compressive strength at different curing ages under two curing regimes—oven curing and ambient curing—with focus on structural reliability and sustainability. The findings are expected to highlight the potential of geopolymer concrete as a durable and environmentally responsible construction material.

Keywords: *Geopolymer concrete, fly ash, alkaline activator, compressive strength*

1. Introduction

1.1. Background

Ordinary Portland cement (OPC) production is a major contributor to global environmental degradation, accounting for nearly 7–8% of total anthropogenic carbon dioxide emissions due to limestone calcination and energy-intensive clink erization processes (Andrew, 2018; Scrivener et al., 2018) [1], [2]. In addition to high greenhouse gas emissions, OPC manufacture consumes large quantities of natural resources and fossil fuels, intensifying concerns regarding sustainability in the rapidly expanding construction sector. Consequently, the development of low-carbon alternatives has become imperative. Fly ash–based geopolymer concrete has emerged as a viable and environmentally sustainable substitute for OPC concrete by utilizing industrial by-products rich in alumino-silicate phases as the primary binder. The geopolymerization process bypasses clinker production, leading to a substantial reduction in CO_2 emissions and energy demand while effectively addressing fly ash disposal issues. Previous studies have demonstrated that, under appropriate curing regimes, fly ash–based geopolymer concrete can achieve mechanical performance comparable to or exceeding that of OPC concrete, reinforcing its potential for large-scale structural and pavement applications (Davidovits, 2015; Provis, 2018) [3], [4].

1.2. Role of Curing in Concrete

Strength development in ordinary Portland cement (OPC) concrete occurs through hydration reactions between cement compounds and water, leading to the formation of calcium silicate hydrate (C–S–H) gel that governs mechanical performance. In contrast, geopolymer concrete (GPC) gains strength through geopolymerization, a polymerization process involving the dissolution of alumino-silicate sources and the formation of a three-dimensional alumino-silicate network. Unlike OPC hydration, geopolymerization is highly sensitive to curing temperature and duration, as elevated temperatures significantly accelerate reaction kinetics and enhance early-age strength, highlighting the critical role of controlled curing regimes in GPC systems (Davidovits, 2015; Provis, 2018).

1.3. Objectives of the Study

- To evaluate strength development of FA-GPC under different curing regimes
- To compare performance with OPC concrete
- To assess feasibility of ambient curing for field applications

1.4. Scope of Study

A controlled experimental comparison was conducted on fly ash–based geopolymer concrete and ordinary Portland cement (OPC) concrete under ambient and oven curing conditions using a unified testing framework. Concrete specimens of grades M25, M30, and M40 were cast, cured for 28 days under different curing regimes, and tested in accordance with ASTM standards. The study provides practical insights into the influence of curing temperature on strength development and the feasibility of ambient curing for geopolymer concrete in real-world construction. The results of this study demonstrate the practical viability of fly ash–based geopolymer concrete under ambient curing conditions, which is critical for in-situ construction where elevated-temperature curing is not feasible. The comparative performance with ordinary Portland cement concrete provides guidance for selecting appropriate curing strategies based on site constraints, energy efficiency, and constructability. These findings support the potential adoption of geopolymer concrete in sustainable real-world construction practices

2. Literature Review

2.1. Fly Ash–Based Geopolymer Concrete (FAGPC)

Fly ash–based geopolymer concrete develops strength through geopolymerization, a reaction mechanism involving the alkaline dissolution of alumino-silicate species from low-calcium fly ash followed by polycondensation into a three-dimensional sodium alumino-silicate hydrate (N-A-S–H) gel network, which acts as the primary binding phase (Davidovits, 2015; Provis, 2018). The kinetics of this reaction are strongly influenced by curing temperature, with elevated-temperature curing significantly accelerating dissolution and gel formation, resulting in enhanced early-age strength and denser microstructures. Studies on low-calcium fly ash geopolymer mortars have further demonstrated that initial heat curing markedly improves strength development compared to ambient curing, confirming the critical role of curing temperature during the early stages of geopolymerization (Sağduyu et al., 2023) [5].

2.2. Curing Methods for GPC

Oven curing of fly ash–based geopolymer concrete involves exposing freshly cast specimens to elevated temperatures, typically between 40 °C and 85 °C, for several hours to accelerate geopolymerization and enhance early-age strength. In contrast, ambient curing relies on room-temperature conditions, which are more practical for in-situ construction but generally result in slower reaction kinetics and delayed strength gain. Reported studies indicate that oven-cured specimens often achieve 20–50% higher early-age compressive strength compared to ambient-cured counterparts, although long-term strength may converge under optimized mix designs; ambient curing, however, remains critical for field applications where heat curing is impractical (Davidovits, 2015; Muhammad et al., 2019; Sağduyu et al., 2023).

2.3. Curing of OPC Concrete

Conventional water curing of ordinary Portland cement (OPC) concrete involves maintaining saturated conditions to ensure continuous hydration of cement particles, which is essential for achieving the desired mechanical properties and durability (Neville, 2012) [6]. Temperature significantly influences this process, as higher curing temperatures

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accelerate hydration and early-age strength development, whereas lower temperatures slow down the reaction and may prolong setting time (Mehta & Monteiro, 2014) [7], [8]. Understanding these effects is critical for designing appropriate curing regimes that optimize strength and service performance in real-world construction [9]-[11].

2.4. Research Gaps Identified

Despite extensive research on both OPC and fly ash–based geopolymer concrete, systematic comparative studies under identical experimental conditions remain scarce. In particular, limited data exist on the efficiency of ambient curing for geopolymer concrete, making it difficult to reliably assess strength development and long-term performance in practical construction scenarios [12], [13]. Standardized investigations are therefore essential to establish clear guidelines for curing regimes and to enable meaningful comparisons between geopolymer and conventional cement-based concretes (Davidovits, 2015; Provis, 2018).

3. Materials and Methods

3.1. Materials

Fly ash used in this study is Class F, sourced from Local supplier with a high silica and alumina content and low calcium oxide, making it suitable for geopolymerization. The alkaline activators consist of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), which facilitate the dissolution of alumino-silicate species and subsequent formation of the geopolymer gel network. Ordinary Portland cement (OPC) of grade 43 was used for comparison with conventional concrete. Natural aggregates conforming to ASTM/IS standards and potable water were employed to prepare all concrete mixes [14].

3.2. Mix Proportions

3.2.1. Materials

Class F fly ash was sourced from [insert source], characterized by high silica and alumina content and low calcium oxide. Alkaline activators, consisting of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), were used to initiate geopolymerization. Ordinary Portland cement (OPC) of [grade, e.g., 43/53] was used for conventional concrete. Coarse and fine aggregates were saturated-surface-dry according to Indian standards, IS:383-1970. Coarse aggregates were obtained in crushed form and were predominantly granite [15]. before weighing coarse and fine aggregates, they were sieved through appropriate sieves and debris was removed along with fine soil. For this research, coarse aggregate was used with nominal sizes of 10mm and 20 mm, and crushed sand was used as fine aggregate. In order to minimize the effects of the aggregates on the properties of concrete, the aggregate was procured from a single source. The physical properties of coarse and fine aggregate were determined by laboratory tests conforming to ASTM/IS standards and potable water were used for all concrete mixes [16].

3.2.2. Mix Proportions

The geopolymer concrete (GPC) mix was designed following established procedures (Davidovits, 2015; Provis, 2018), optimizing the binder content, activator concentration, and water-to-binder ratio to achieve target workability and strength. OPC concrete mixes were prepared according to IS 10262:2019 guidelines, considering target compressive strength, water–cement ratio, and aggregate grading. Both GPC and OPC mixes were adjusted to ensure comparable workability and slump. NaOH solution was prepared one day before casting ,13M solution is considered here.

3.3. Specimen Preparation

Concrete specimens of grades M25, M30, and M40 were cast in standard moulds of size 150 mmX150m MmX150mm. The mixing procedure for geopolymer concrete involved first preparing the alkaline activator solution by combining NaOH and Na_2SiO_3, which was then allowed to equilibrate for 24 hours. Fly ash was dry-mixed with aggregates before gradually adding the activator solution to achieve a homogeneous mix. For OPC concrete, cement, aggregates, and water were mixed using a conventional mechanical mixer until uniform consistency was obtained. Concrete was then cast into standard molds in layers and compacted using a table vibrator to remove entrapped air, ensuring uniform density and proper consolidation.

3.4. Testing Program

- Compressive strength for test ages (e.g., 3, 7, 14, 28 days) is taken on compression testing machine (Figure 1).

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Figure 1 Casting of Concrete Specimens

3.5. Curing Regimes

- GPC specimens were subjected to ambient and oven curing at 80 °C for 24 hours, while OPC specimens underwent conventional water curing. All specimens were tested after 28 days for compressive strength as per ASTM standards (Figure 2).

Figure 2 Cube Testing

4. Results

4.1. Compressive Strength Development

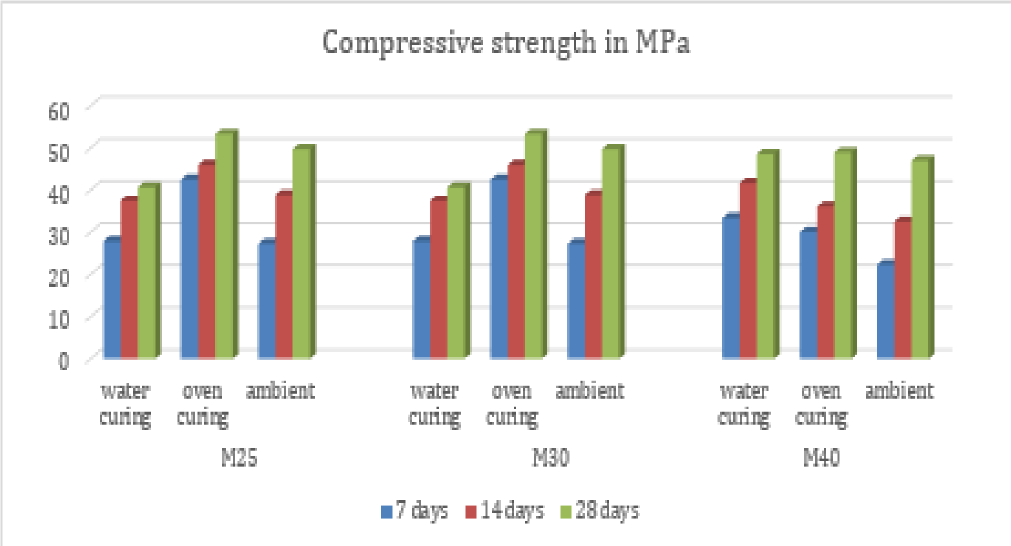

Figure 3 Compressive Strength Comparison of M25, M30, and M40 Concrete Under Different Curing Conditions (7, 14, and 28 Days)

It is clearly observed from the graph compressive strength for geopolymer concrete strength gaining process is slow but ultimately gives higher performance at 28 days greater than conventional concrete (Figure 3).

4.1.1. Key Observations

- Oven curing drastically accelerates strength development in GPC at early ages.
- Ambient curing gives slower early strength but can reach similar 28-day strength if mix is well-designed.
- OPC gains strength more predictably under ambient curing; heat curing is not required.

4.2. Comparative Performance of GPC and OPC

4.2.1. Key Observations

- **Early-Age Strength:**
  - OPC: Moderate, sufficient for normal construction cycles.
  - GPC: Highly dependent on curing; heat curing essential for early use.
- Long-Term Strength:
  - Both OPC and GPC reach similar 28-day strength.
  - GPC often shows slower initial gain under ambient conditions, but may exceed OPC strength at later ages due to continued geopolymerization.
- Strength Curve Comparison (Qualitative):
  - **OPC:** Smooth S-shaped curve, steady early and long-term growth.
  - **FAGPC Ambient:** Slow initial rise, catches up by 28 days.
  - **FAGPC Heat-Cured:** Rapid early rise, plateau reached sooner.

4.3. Effect of Curing Temperature

4.3.1. Polymerization Acceleration in Oven Curing

Geopolymer concrete develops strength through geopolymerization, involving a chemical reaction between an aluminosilicate source such as fly ash and alkaline activators (NaOH and Na_2SiO_3). Oven or heat curing at around 80 °C significantly accelerates this process by enhancing the dissolution of silica and alumina from fly ash particles, leading to rapid formation of N-A-S-H geopolymer gel. This

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accelerated gel formation results in early microstructural densification and consequently higher early-age strength

4.3.2. Effect on Strength

Under ambient curing conditions, geopolymer concrete exhibits relatively low early-age strength at 3–7 days, typically attaining only about 20–50% of its 28-day strength when compared with oven-cured specimens. However, with optimized mix design and appropriate curing control, the 28-day compressive strength of ambient-cured geopolymer concrete can be comparable to that of conventional OPC concrete.

4.3.3. Ambient Curing Efficiency

At room temperature (approximately 25–30 °C), the geo-polymerization process proceeds at a relatively slow rate, resulting in gradual dissolution of fly ash particles and progressive formation of geo-polymeric gel. Consequently, strength development is delayed during early ages but continues steadily over time. Under such ambient curing conditions, significant strength gain is observed up to 28 days and may extend beyond, owing to sustained geo-polymerization and matrix densification.

4.3.4. Advantages

Ambient-cured geopolymer concrete is energy-efficient as it eliminates the need for artificial heat curing, thereby reducing energy consumption. It is particularly practical for in-situ applications such as pavements, slabs, and structural elements where oven curing is not feasible. Consequently, this curing approach enhances the sustainability and scalability of geopolymer concrete for large-scale construction projects.

4.3.5. Limitations

A key limitation of ambient-cured geopolymer concrete is its slow early-age strength development, which may lead to delays in construction schedules. Additionally, proper curing practices—such as maintaining a moist environment and protecting the surface from premature drying—are essential to ensure adequate strength and durability development.

5. Discussion

5.1. Mechanism of Strength Development

Concrete gains strength through chemical reactions, but the processes differ between OPC and geopolymer concrete. In OPC, hydration occurs when cement reacts with water to form calcium silicate hydrate gel, which gradually binds the aggregates and develops strength over 28 days. In Fly ash based geopolymer concrete (FAGPC), geo-polymerization takes place as aluminosilicate materials react with alkaline activators, forming a three-dimensional N–A–S–H gel network. This reaction is highly temperature-dependent: ambient curing is slow, while heat curing accelerates early strength gain. Unlike OPC, GPC offers environmental benefits by reducing carbon emissions, making it a sustainable alternative.

5.2. Practical Implications

Ambient-cured geopolymer concrete is well suited for field-cast applications such as in-situ pavements, slabs, and foundations, particularly in large-scale projects where heat or steam curing is impractical. From a sustainability and cost perspective, the absence of external energy requirements reduces both operational costs and carbon footprint, aligning GPC with green construction practices and offering advantages over OPC. However, lower early-age strength necessitates careful construction scheduling, as formwork removal and load application may need to be delayed compared to OPC or heat-cured GPC. Furthermore, strict quality control through consistent curing practices—especially moisture retention and protection from premature drying—is essential to achieve the desired 28-day strength and long-term performance

5.3. Sustainability Perspective

Geopolymer concrete (GPC) offers substantial environmental benefits by significantly reducing CO_2 emissions compared to ordinary Portland cement, making it a sustainable construction material. For large-scale applications, ambient-cured GPC is well suited to in-situ construction without incurring additional energy costs, while oven-cured GPC is more appropriate for precast, modular, and accelerated construction projects where rapid early-age strength development is essential.

Conclusions

OPC concrete demonstrates predictable and steady strength development, making it suitable for conventional cast-in-situ construction. Ambient-cured GPC exhibits delayed early-age strength, which can limit its applicability in projects requiring early loading; however, its continued geopolymerization enables comparable or superior long-term strength performance. Heat-cured GPC shows significantly enhanced early-age strength and reaches its strength plateau earlier, indicating strong potential for precast elements and accelerated construction practices.

Limitations and Future Scope

Long-term performance of geopolymer concrete must be established through durability tests such as resistance to chloride ingress, sulphate and acid attack, carbonation, shrinkage, and abrasion under aggressive exposure conditions. Microstructural analysis using SEM, XRD, and FTIR is essential to understand reaction products, gel formation, and matrix densification governing strength and durability. Additionally, field-scale validation through pilot projects or in-situ applications is necessary to confirm laboratory findings and assess constructability, curing feasibility, and long-term service behavior under real environmental and loading conditions.

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