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Experimental Study on the Effect of Curing Conditions on the Strength Development of Geo-Polymer Concrete

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Abstract - *The environmental impact associated with the production of ordinary Portland cement has encouraged the development of geo polymer concrete as a sustainable construction material. This study presents an experimental investigation on the effect of curing conditions on the strength development of geo polymer concrete. Fly ash–based and fly ash–GGBS blended geo polymer concrete mixes were prepared using sodium hydroxide and sodium silicate as alkaline activators. Two curing regimes, namely ambient curing and heat curing at elevated temperatures, were adopted to evaluate their influence on mechanical properties. Fresh properties were assessed in terms of workability, while hardened properties were evaluated through compressive, split tensile, and flexural strength tests at different curing ages. The results indicate that fly ash–based mixes exhibited higher workability, whereas the incorporation of GGBS reduced workability due to rapid reaction kinetics. Heat-cured geo polymer concrete achieved significantly higher early-age and 28-day strength, while ambient-cured fly ash–GGBS mixes attained strength comparable to conventional concrete. The study confirms that curing conditions play a critical role in geo polymerization and strength development.*

Key Words: **Geo polymer concrete; Curing conditions; Fly ash; Ground granulated blast furnace slag (GGBS); Ambient curing; Heat curing; Strength development; Sustainable construction materials**

1. INTRODUCTION

The construction industry is one of the largest consumers of natural resources and energy worldwide. Concrete, being the most widely used construction material, plays a vital role in infrastructure development. However, the extensive use of ordinary Portland cement (OPC) as the primary binder in concrete has raised serious environmental and sustainability concerns. This has led researchers to explore alternative binding materials that can reduce environmental impact while maintaining acceptable mechanical performance. In this context, geo polymer concrete has emerged as a promising sustainable alternative to conventional OPC-based concrete.

1.1. BACKGROUND AND MOTIVATION

1.1.1. Environmental Impact of OPC Production

The production of ordinary Portland cement is an energy-intensive process that involves the calcination of limestone and the combustion of fossil fuels at very high temperatures, typically around 1450°C. This process releases a significant amount of carbon dioxide into the atmosphere, both from fuel combustion and from the decomposition of limestone. It is estimated that cement manufacturing alone contributes nearly 7–8% of global CO_2 emissions, making it a major contributor to climate change. In addition to greenhouse gas emissions, cement production consumes large quantities of natural resources and energy, further aggravating environmental degradation.

1.1.2 Need for Sustainable Alternatives in Concrete Technology

Growing environmental awareness and stricter regulations on carbon emissions have created an urgent need for sustainable alternatives to OPC-based concrete. The utilization of industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS) not only reduces cement consumption but also addresses issues related to waste disposal. Sustainable concrete technologies aim to minimize environmental impact while ensuring adequate strength, durability, and service life. Geo polymer concrete represents one such alternative that aligns with the principles of sustainable development and circular economy.

1.2 GEOPOLYMER CONCRETE AS A SUSTAINABLE BINDER

1.2.1 Concept of Geo polymerization

Geo polymerization is a chemical process in which alumino-silicate materials react with alkaline activators to form a hardened binder. Unlike OPC concrete, which gains strength through hydration reactions, geo polymer concrete develops strength through polymeric reactions involving silica and alumina species. Under alkaline conditions, these species dissolve and reorganize into a three-dimensional alumino-silicate network, resulting in a strong and stable binding matrix. This process eliminates the need for cement and significantly reduces carbon emissions associated with concrete production.

1.2.2 Role of Alumino-Silicate Materials and Alkaline Activators

Alumino-silicate source materials such as fly ash and GGBS play a critical role in geo polymer concrete. Fly ash, rich in silica and alumina, contributes to long-term strength

development, while GGBS, containing higher calcium content, enhances early-age strength and enables ambient curing. Alkaline activators, typically sodium hydroxide and sodium silicate solutions, initiate the dissolution of silica and alumina from the source materials and facilitate the geo polymerization process. The type, concentration, and proportion of these activators significantly influence reaction kinetics, strength development, and curing requirements.

1.3 IMPORTANCE OF CURING IN GEOPOLYMER CONCRETE

1.3.1 Difference between OPC Hydration and Geo polymerization

Curing plays a fundamentally different role in geo polymer concrete compared to OPC concrete. In OPC concrete, curing primarily ensures continuous hydration by maintaining adequate moisture, leading to the formation of calcium silicate hydrate (C–S–H) gel. In contrast, geo polymer concrete does not rely on hydration; instead, curing promotes geo polymerization by providing favorable thermal and chemical conditions. As a result, temperature rather than moisture becomes the dominant factor influencing strength development in geo polymer systems.

1.3.2 Limitations of Conventional Water Curing

Conventional water curing methods, which are essential for OPC concrete, are not always suitable for geo polymer concrete. Water curing may lead to leaching of alkaline activators, thereby reducing the alkalinity required for effective geo polymerization. This can result in incomplete polymerization and lower strength development. Furthermore, excessive moisture does not significantly contribute to geo polymer reactions, highlighting the limitations of applying traditional curing practices to geo polymer concrete.

1.3.3 Role of Temperature and Curing Environment

Temperature plays a crucial role in controlling the rate and extent of geo polymerization. Elevated temperature curing accelerates the dissolution of alumino-silicate materials and enhances early-age strength development, particularly in fly ash-based geo polymer concrete. Ambient curing is feasible when calcium-rich materials such as GGBS are incorporated. The curing environment, whether sealed or open, also affects the retention of alkaline solution and overall strength performance. Therefore, curing conditions must be carefully optimized for geo polymer concrete.

1.4 RESEARCH GAP

1.4.1 Need for Systematic Comparison of Curing Regimes

Although numerous studies have investigated geo polymer concrete, many focus on a single curing method or vary multiple parameters simultaneously. There is a lack of systematic experimental studies comparing different curing regimes under identical mix proportions. This makes it difficult to isolate the specific influence of curing conditions on strength development and limits the reliability of reported conclusions.

1.4.2 Limited Field-Relevant Studies on Ambient Curing

Most existing research emphasizes heat curing due to its effectiveness in achieving high early-age strength. However, heat curing is impractical for most cast-in-situ construction. Limited studies have focused on ambient curing strategies that are feasible for field applications. This gap highlights the need for experimental investigations that evaluate ambient curing performance, particularly for blended geo polymer systems.

1.5 OBJECTIVE OF THE STUDY

The primary objective of the present study is to experimentally evaluate the effect of curing conditions on the strength development of geo polymer concrete. The study aims to compare ambient curing and heat curing regimes using fly ash and fly ash–GGBS based geo polymer concrete mixes. By assessing early-age and later-age strength characteristics, the research seeks to identify curing conditions that provide a balance between mechanical performance and practical applicability, thereby supporting the wider adoption of geo polymer concrete in sustainable construction.

2 MATERIALS AND METHODS

This section describes the materials used and the experimental methodology adopted to investigate the effect of curing conditions on the strength development of geo polymer concrete. A systematic approach was followed for material selection; mix proportioning, specimen preparation, curing, and testing in order to ensure reliability and reproducibility of results. The procedures adopted were based on established practices reported in previous geo polymer concrete research.

2.1 MATERIALS

2.1.1 Alumino-Silicate Source Materials

Fly ash and ground granulated blast furnace slag (GGBS) were used as the primary binder materials in the present study. Low-calcium Class F fly ash was selected due to its high silica and alumina content, which is suitable for geo polymerization. Fly ash contributes to improved workability and long-term strength development. GGBS, being a calcium-rich material, was incorporated to enhance early-age strength and enable effective ambient curing. The combination of fly ash and GGBS was adopted to study the influence of calcium content on strength development under different curing conditions.

2.1.2 Alkaline Activator Solutions

Alkaline activators consisting of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions were used to initiate the geo polymerization process. Sodium hydroxide solution was prepared at a predetermined molarity using laboratory-grade pellets and potable water, while commercially available sodium silicate solution was used. The activator solutions play a critical role in dissolving silica and alumina from the source materials and facilitating polymeric chain formation.

2.1.3 Aggregates

Locally available fine and coarse aggregates were used in the geo polymer concrete mixes. Natural river sand conforming to standard grading requirements was used as fine aggregate, while crushed stone aggregates of nominal size were used as coarse aggregate. Aggregates constitute the major volume of concrete and primarily contribute to strength through load transfer and interlocking. Their properties were maintained similar to those used in conventional concrete to ensure comparability of results.

Table 1: Materials Used in the Study

Material	Description	Role in Geo polymer Concrete
Fly ash (Class F)	Low calcium, rich in Si and Al	Primary geo polymer binder
GGBS	Calcium-rich industrial by-product	Enhances early strength
Sodium hydroxide	Alkaline activator	Dissolution of alumino-silicates
Sodium silicate	Silica-rich activator	Polymer network formation

2.2 MIX PROPORTIONING

2.2.1 Binder Composition

Geo polymer concrete mixes were prepared using fly ash alone and fly ash–GGBS blended binder systems. The binder composition was selected to evaluate the influence of calcium content on strength development under different curing conditions. Fly ash-based mixes were primarily used to assess heat curing performance, while fly ash–GGBS blends were used to evaluate ambient curing feasibility.

2.2.2 Activator Molarity and Na_2SiO_3/NaOH Ratio

The molarity of the sodium hydroxide solution was selected based on previous research findings to ensure adequate geo polymerization. Sodium silicate was combined with sodium hydroxide in a fixed ratio to enhance polymer formation. The Na_2SiO_3/NaOH ratio was maintained within an optimal range to balance workability and strength development.

2.2.3 Activator-to-Binder Ratio

The activator-to-binder ratio was maintained constant for all mixes to isolate the effect of curing conditions. This ratio governs the availability of alkaline solution required for dissolution and polymerization. An optimum ratio was selected to ensure sufficient geo polymer reaction without causing excessive porosity or loss of workability.

2.3 SPECIMEN PREPARATION

2.3.1 Mixing Procedure

Geo polymer concrete was prepared by first dry mixing the binder materials and aggregates to ensure uniform distribution. The pre-prepared alkaline activator solution was then added gradually, and mixing was continued until a homogeneous and workable mix was obtained. Proper mixing is essential to promote uniform geo polymerization throughout the concrete matrix.

2.3.2 Casting and Compaction

The fresh geo polymer concrete was placed into standard moulds in layers and compacted using appropriate compaction techniques to remove entrapped air. Proper compaction ensured uniform density and minimized voids, which directly influence strength development.

Figure-1: CST of Geo-polymer Concrete

2.3.3 De moulding

Specimens were de moulded after the initial setting period. Care was taken during de moulding to prevent surface damage. After de moulding, specimens were immediately transferred to their respective curing environments.

2.4 CURING REGIMES

2.4.1 Ambient Curing

Ambient curing was carried out by storing the specimens at room temperature under laboratory conditions. This curing regime was adopted to evaluate the practical applicability of geo polymer concrete in field conditions, particularly for mixes containing GGBS.

2.4.2 Heat Curing

Heat curing was performed by placing the specimens in a controlled curing chamber or oven at elevated temperatures for a specified duration. Heat curing accelerates the geo polymerization process and enhances early-age strength, especially in fly ash-based geo polymer concrete.

2.5 TESTING PROGRAM

2.5.1 Workability

Workability of fresh geo polymer concrete was assessed using standard test methods such as slump test. Workability evaluation helped in understanding the effect of binder composition and activator content on fresh concrete behavior.

2.5.2 Compressive Strength Testing

Compressive strength tests were conducted at specified curing ages using a calibrated compression testing machine. Compressive strength was considered the primary parameter to assess the influence of curing conditions on geo polymer concrete performance.

2.5.3 Split Tensile and Flexural Strength Tests

Where applicable, split tensile strength and flexural strength tests were performed to evaluate the tensile behavior and cracking resistance of geo polymer concrete under different curing regimes.

3. RESULTS AND DISCUSSION

This section presents and discusses the experimental results obtained from the investigation on geo polymer concrete under different curing conditions. The influence of curing regime and binder composition on compressive strength development is analyzed in detail. The results are interpreted to understand strength development behavior at early and later ages and to assess the feasibility of geo polymer concrete as a sustainable alternative to conventional concrete.

3.1 EFFECT OF CURING CONDITIONS ON COMPRESSIVE STRENGTH

3.1.1 Comparison between Ambient Curing and Heat Curing

The compressive strength results indicate a significant influence of curing conditions on the performance of geo polymer concrete. Heat-cured specimens consistently exhibited higher compressive strength compared to ambient-cured specimens at all testing ages. Elevated temperature curing accelerates the geo polymerization process by enhancing the dissolution of silica and alumina from the source materials, leading to rapid formation of a dense geo polymer matrix. In contrast, ambient curing resulted in comparatively lower strength due to slower reaction kinetics, particularly in fly ash-based mixes. These observations confirm that curing temperature is a dominant factor governing strength development in geo polymer concrete.

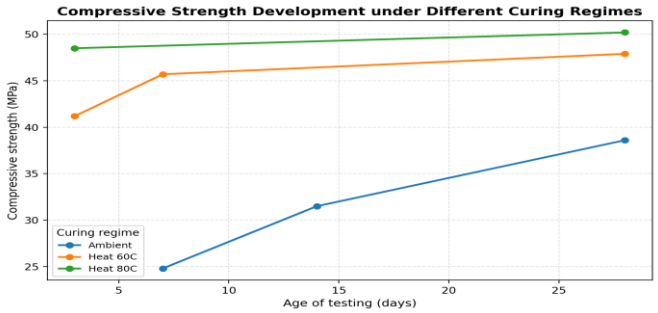

Figure-2: Compressive Strength of Geo polymer Concrete under Different Curing Conditions

3.1.2 Early-Age versus 28-Day Strength Behaviour

At early ages, heat-cured geo polymer concrete achieved a substantial portion of its 28-day compressive strength, indicating rapid strength gain. This behavior is attributed to accelerated polymerization under elevated temperature conditions. Ambient-cured specimens showed relatively lower early-age strength; however, continuous strength gain was observed with increasing age. By 28 days, ambient-cured mixes, particularly those containing GGBS, attained compressive strength comparable to conventional OPC concrete. This trend highlights the potential of geo polymer concrete to develop adequate long-term strength even under ambient curing.

3.2. INFLUENCE OF BINDER COMPOSITION

3.2.1 Fly Ash versus Fly Ash–GGBS Systems

The binder composition significantly influenced the compressive strength of geo polymer concrete. Fly ash-based geo polymer concrete exhibited higher workability but showed slower strength development under ambient curing

conditions. In contrast, fly ash–GGBS blended systems demonstrated enhanced strength development at both early and later ages. The incorporation of GGBS improved the reactivity of the binder system, resulting in higher compressive strength under ambient curing. Heat-cured fly ash-based mixes, however, performed exceptionally well, confirming the suitability of fly ash systems under elevated temperature curing.

3.2.2 Role of Calcium in Ambient Curing Performance

The presence of calcium in GGBS played a crucial role in improving the ambient curing performance of geo polymer concrete. Calcium contributes to the formation of additional binding phases such as calcium-alumino-silicate-hydrate (C-A-S-H) gel alongside geo polymer gel. This dual binding mechanism enhances early-age strength and reduces dependency on heat curing. As a result, fly ash–GGBS geo polymer concrete exhibited superior strength development under ambient curing compared to fly ash-only systems, making it more suitable for field applications.

3.3 STRENGTH DEVELOPMENT TRENDS

3.3.1 Rate of Strength Gain Under Different Curing Regimes

The rate of strength gain varied significantly with curing regime. Heat-cured specimens showed rapid strength development within the initial curing period, with marginal strength gain at later ages. Ambient-cured specimens exhibited gradual but continuous strength development over time. This behavior indicates that while heat curing is effective for achieving high early strength, ambient curing allows sustained geo polymerization and long-term strength gain, particularly in calcium-rich systems.

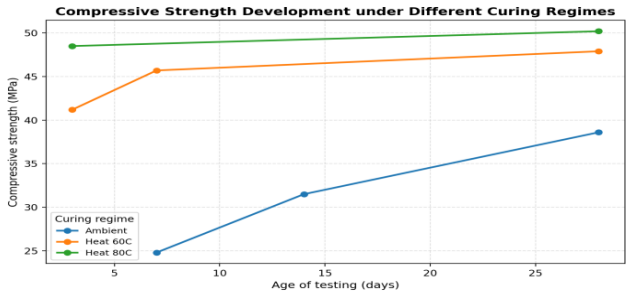

Figure-3: Compressive Strength of Geo polymer Concrete under Different Curing Conditions

3.3.2 Comparison with OPC Concrete Benchmarks

When compared with conventional OPC concrete, heat-cured geo polymer concrete demonstrated comparable or higher compressive strength at early ages. Ambient-cured fly ash–GGBS geo polymer concrete achieved compressive strength values similar to OPC concrete at 28 days. These results suggest that geo polymer concrete, when properly designed and cured, can meet structural strength requirements while offering significant environmental benefits. The findings support the feasibility of geo polymer concrete as a sustainable alternative to OPC-based concrete for practical construction applications.

4. CONCLUSION

This experimental study evaluated the effect of curing conditions on the strength development of geo polymer concrete using fly ash and fly ash–GGBS binder systems. The results demonstrate that curing regime significantly influences the geo polymerization process and mechanical performance. Heat-cured geo polymer concrete exhibited rapid strength development and achieved higher early-age and 28-day compressive strength, particularly in fly ash-based mixes. Ambient curing resulted in comparatively lower early-age strength; however, fly ash–GGBS blended systems showed substantial improvement due to the presence of calcium, which enhanced reaction kinetics and enabled effective strength gain at room temperature. The study confirmed that geo polymer concrete can achieve compressive strength comparable to conventional OPC concrete when appropriate binder composition and curing conditions are adopted. Heat curing is effective for precast applications, while ambient-cured fly ash–GGBS geo polymer concrete offers practical feasibility for cast-in-situ construction. Overall, the findings support the potential of geo polymer concrete as a sustainable and environmentally friendly alternative to OPC-based concrete.

5. LIMITATIONS OF THE STUDY

The present study has certain limitations that should be considered while interpreting the results. The experimental investigation focused primarily on strength-related properties, while long-term durability aspects such as resistance to chemical attack, permeability, shrinkage, and creep were not evaluated. Microstructural characterization using techniques such as SEM or XRD was not conducted, limiting detailed understanding of geo polymerization mechanisms. The study considered a limited range of curing temperatures and durations, which may not represent all field conditions. Additionally, the mix proportions and activator concentrations were kept constant, and the effect of varying molarity or activator ratios was not examined. Field-scale validation and performance under real environmental exposure were also beyond the scope of the present investigation.

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