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EFFECT OF CURING REGIMES ON THE COMPRESSIVE STRENGTH OF FLY ASH–GGBS BASED GEOPOLYMER CONCRETE INCORPORATING RECYCLED AGGREGATES

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Research Paper

ABSTRACT

The curing regime plays a critical role in the strength development of geopolymer concrete (GPC), particularly when incorporating industrial by-products and recycled aggregates. This study investigates the influence of different curing methods on the compressive strength of fly ash–GGBS based geopolymer concrete with partial replacement of natural coarse aggregates by recycled aggregates. Three curing conditions—ambient curing, oven curing, and hot water curing (accelerated curing)—were adopted to evaluate their effect on strength development. Concrete mixes with a constant binder composition and alkaline activator ratio were prepared and tested for compressive strength at 7 and 28 days. The results indicate that accelerated curing methods significantly enhance early-age strength due to improved geopolymerization kinetics, with oven curing exhibiting the highest strength at both ages, followed by steam curing, while ambient curing showed slower but continuous strength development over time. The incorporation of recycled aggregates resulted in a marginal reduction in compressive strength; however, the values remained within acceptable structural limits. Overall, the study highlights that appropriate curing strategies can effectively optimize the performance of sustainable geopolymer concrete, making it a viable alternative for structural applications.

KEYWORDS: Fly Ash, GGBS, Accelerated Curing, Geopolymer Concrete

INTRODUCTION

The construction industry is undergoing a significant transition toward sustainable materials to reduce the environmental impact associated with conventional Portland cement. Ordinary Portland cement (OPC) production is responsible for substantial carbon dioxide emissions, prompting the need for alternative binders with lower environmental footprints. In this context, geopolymer concrete (GPC),[1] synthesized from aluminosilicate-rich industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), has emerged as a promising sustainable construction material. GPC not only reduces greenhouse gas emissions but also offers comparable or superior mechanical properties to conventional concrete.[2]

One of the critical factors influencing the performance of geopolymer concrete is the curing regime. Unlike OPC-based systems, geopolymerization is a temperature-dependent chemical process, and the rate of reaction is significantly affected by curing conditions.[3] Accelerated curing methods, such as oven curing and steam curing, are known to enhance early-age strength by promoting rapid dissolution and polymerization of source materials.[4] In contrast, ambient curing conditions may result in slower strength development, particularly in low-calcium systems. Therefore, understanding the influence of different curing types on strength development is essential for the practical implementation of geopolymer concrete.

In addition to binder sustainability, the incorporation of recycled aggregates further contributes to resource conservation and waste reduction. However, the use of recycled aggregates can influence the mechanical performance of concrete due to their inherent properties,[5] such as higher absorption and weaker interfacial transition zones. The combined effect of curing conditions and recycled aggregate incorporation on the compressive strength of geopolymer concrete remains an area requiring further investigation.[6]

Although several studies have examined the effects of curing regimes and recycled aggregates independently, limited research has focused on their combined influence in fly ash–GGBS based geopolymer systems. Addressing this gap is important for developing optimized mix designs and curing strategies that ensure both sustainability and structural performance.

Therefore, the present study aims to investigate the effect of different curing types—ambient curing, oven curing, and steam-assisted curing—on the compressive strength of fly ash–GGBS-based geopolymer concrete with partial replacement of natural aggregates by recycled aggregates. The findings are expected to provide insights into selecting appropriate curing methods for enhancing the performance of sustainable geopolymer concrete in practical applications.

LITERATURE REVIEW

Previous studies have established that curing conditions significantly influence the mechanical performance of geopolymer concrete (GPC). Accelerated curing methods, particularly heat or steam curing, enhance the geopolymerization process by increasing reaction kinetics, leading to higher early-age compressive strength compared to ambient curing.[7] It has been reported that heat-cured GPC can achieve compressive strengths exceeding 50 MPa at 28 days, whereas ambient-cured systems generally exhibit slower strength development due to reduced reaction rates.[8] Similarly, accelerated curing techniques have been shown to significantly improve compressive, tensile, and flexural strengths by promoting faster dissolution and polymerization of aluminosilicate materials.

However, ambient curing remains attractive for practical applications due to ease of implementation. Studies indicate that the incorporation of calcium-rich materials such as GGBS can improve strength development even under ambient conditions, partially compensating for the lack of induced activation.[9]

With respect to recycled aggregates, their inclusion in geopolymer concrete contributes to sustainability but often leads to a reduction in compressive strength due to higher water absorption and weak interfacial transition zones.[6][10] Increasing recycled aggregate content generally decreases strength; however, values remain within acceptable structural limits for moderate replacement levels. Additionally, durability and strength performance can be improved through proper mix design and supplementary materials.[11] Although extensive research exists on curing regimes and recycled aggregate incorporation independently, limited studies have investigated their combined influence on the compressive strength of fly ash–GGBS based geopolymer concrete. Therefore, a comparative evaluation of different curing types in conjunction with recycled aggregate replacement is necessary to develop optimized and sustainable mix designs.

MATERIALS AND METHODS

Materials

Class F fly ash and ground granulated blast furnace slag (GGBS) were used as the primary aluminosilicate binders for the preparation of geopolymer concrete. The fly ash served as the low-calcium source material, while GGBS contributed to improved early-age strength due to its calcium content. Natural river sand was used as fine aggregate, and crushed stone was used as coarse aggregate. Recycled coarse aggregates (RCA), obtained from processed construction and demolition waste, were used as partial replacement of natural coarse aggregates at a selected percentage level.

The alkaline activator solution consisted of a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The NaOH solution of a predetermined molarity was prepared 24 hours prior to mixing to ensure complete dissolution. The sodium silicate solution was then mixed with NaOH solution to form the activator.

Mix Proportion

The geopolymer concrete mix was designed by maintaining a constant binder composition of fly ash and GGBS at a selected ratio. The alkaline activator-to-binder ratio and sodium silicate-to-sodium hydroxide ratio of 1:2.5 were kept constant throughout the study to isolate the effect of curing conditions. A suitable water-to-binder ratio of 0.45 was maintained to achieve the desired workability. Recycled aggregates were incorporated as a partial replacement of natural coarse aggregates at a fixed percentage of 30% and these numbers were achieved based on specific gravity of aggregates. Table 1 gives the details of basic material testing results.

Table 1 : Quantity of materials for the mix

Material	Quantity
Fly Ash (70%)	280 kg
GGBS (30%)	120 kg
Total Binder	400 kg
Fine Aggregate	650 kg
Coarse Aggregate	1200 kg
Recycled Aggregate (30%)	360 kg
Natural Coarse Aggregate	840 kg
Alkaline Activator Solution	180 kg
Sodium Hydroxide (NaOH) Solution	128.6 kg
Sodium Silicate (Na_2SiO_3) Solution	51.4 kg

Curing Regimes

Three different curing methods were adopted to study their influence on compressive strength development:

- Ambient curing: Specimens were kept at room temperature (approximately 25–30°C) until the testing age.
- Oven curing: Specimens were cured in a hot air oven at a controlled temperature range of 60–80°C for a specified duration.
- Accelerated curing: Specimens were exposed to hot water for 3.5 hours and then left in hot water for 24 hours and then cured in room temperature. [12]

Testing

Compressive strength tests were conducted on geopolymer concrete specimens at selected curing ages, typically at 7 and 28 days. The tests were performed using a compression testing machine in accordance with relevant standards. The average of three specimens was reported for each test condition to ensure accuracy and consistency of results.

RESULTS AND DISCUSSION

The compressive strength results of geopolymer concrete under different curing regimes are presented in Table 3 and illustrated in Figures 1–3. The results clearly indicate that curing conditions play a decisive role in the strength development of geopolymer systems.

Effect of Curing Type on Compressive Strength

The compressive strength values show a strong dependence on the type of curing adopted. At 7 days, oven-cured geopolymer concrete achieved the highest strength of 35.6 MPa, followed by accelerated -cured concrete at 30.2 MPa, while ambient-cured specimens recorded the lowest strength of 18.5 MPa. The strength of oven-cured specimens was nearly 1.9 times higher than ambient curing, highlighting the effectiveness of elevated temperature in accelerating geopolymerization.

Accelerated-curing also significantly improved early-age strength compared to ambient curing, though it remained approximately 15–18% lower than oven curing, which may be attributed to less uniform heat transfer and variations in moisture distribution during the curing process. At 28 days, a similar trend was observed, with oven curing producing the highest compressive strength of 48.2 MPa, followed by accelerated curing (44.5 MPa) and ambient curing (32.8 MPa). While the gap between curing methods reduced over time, oven curing consistently maintained superior performance, indicating that early thermal activation contributes to long-term strength gain as well.

The relatively lower strength observed in ambient curing can be attributed to slower reaction kinetics and incomplete geopolymerization during the initial stages. However, the presence of GGBS in the binder system contributed to continued strength development at later ages due to calcium-assisted reaction mechanisms.

Strength Development Trends and Geopolymerization Behavior

The strength development trend clearly demonstrates that geopolymer concrete exhibits a temperature-dependent reaction mechanism. Accelerated curing conditions (oven and hot water) significantly enhance the dissolution of aluminosilicate precursors (fly ash and GGBS), leading to rapid formation of geopolymeric gels such as N–A–S–H and C–A–S–H. This results in dense microstructure formation and higher early-age strength.

From 7 to 28 days, ambient-cured geopolymer concrete showed the highest percentage increase in strength, rising from 18.5 MPa to 32.8 MPa, which corresponds to an increase of approximately 77%. In comparison, oven-cured specimens exhibited an increase of about 35%, while steam-cured specimens showed approximately 47% growth over the same period.

This indicates that although accelerated curing leads to rapid early strength gain, the rate of strength development slows down at later ages due to the early completion of major geopolymerization reactions. On the other hand, ambient curing allows for gradual and continuous reaction over time, resulting in sustained strength gain.

The inclusion of GGBS plays a crucial role in improving strength development under all curing conditions. The calcium content in GGBS facilitates additional formation of calcium-alumino-silicate-hydrate (C–A–S–H) gel, which complements the geopolymeric network and enhances overall mechanical performance, particularly under ambient conditions.

Overall, the observed trends confirm that curing temperature significantly influences both the rate and extent of geopolymerization, thereby governing the strength development behavior of geopolymer concrete.

Figure 1: Compressive Strength of Geopolymer Concrete under Different Curing Regimes

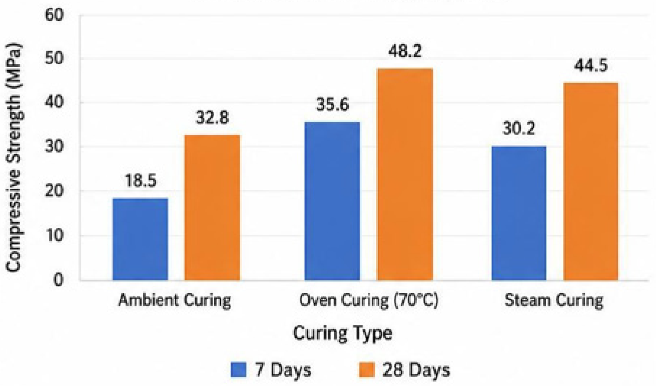


Figure 2: Comparison of Compressive Strength between Geopolymer Concrete and OPC Concrete

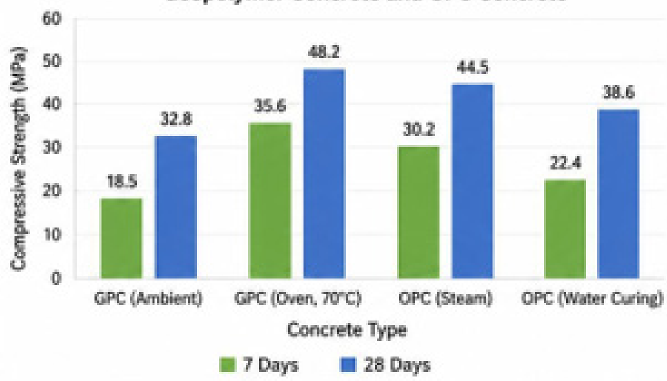
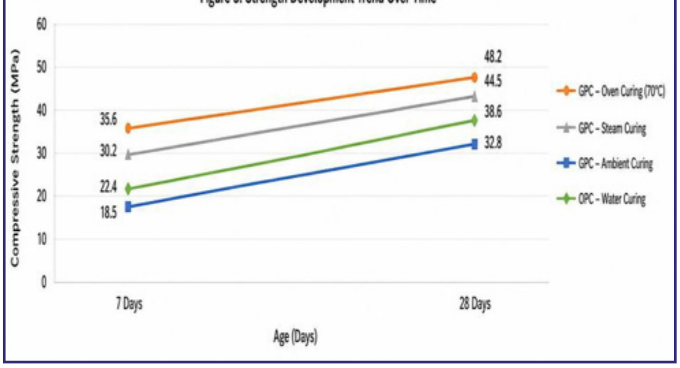


Figure 3: Strength Development Trend Over Time



CONCLUSIONS

- Curing regime has a significant influence on the compressive strength of geopolymer concrete.
- Oven curing resulted in the highest early-age and overall compressive strength among the curing methods studied.
- Ambient curing exhibited slower strength development but showed gradual improvement over time.
- The incorporation of recycled aggregates led to a marginal reduction in strength; however, the performance remained within acceptable

structural limits.

- Accelerated curing techniques are effective in enhancing early strength, making geopolymer concrete suitable for rapid construction applications.

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