Geo-Polymer Concrete: An Experimental Approach Toward Sustainable Construction

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Abstract—**Geo-polymer concrete (GPC) is an innovative and eco-friendly alternative to traditional Portland cement-based concrete, designed to reduce carbon emissions by utilizing industrial by-products such as fly ash, slag, and rice husk ash. This project investigates the properties, applications, and environmental benefits of GPC, focusing on its potential as a sustainable construction material.__Geo-polymer concrete is produced by activating aluminosilicate materials (e.g., fly ash) with an alkaline solution, which binds the materials into a cohesive matrix. Unlike conventional concrete, GPC does not require high temperature processing and has a significantly lower carbon footprint, as it eliminates the need for calcination. The research conducted in this project assesses the mechanical properties, durability, and resistance to harsh environmental conditions of GPC. Factors such as curing temperature, alkaline solution concentration, and mix ratios are varied to understand their impact on the strength and performance of the final product._The project results highlight that GPC can achieve compressive strengths comparable to traditional concrete and exhibits superior resistance to chemical attacks, making it suitable for applications in aggressive environments. Additionally, GPC's rapid setting time and reduced need for water make it an appealing choice for construction in arid regions._In conclusion, geo-polymer concrete emerges as a viable, sustainable construction material that not only meets the strength and durability standards of conventional concrete but also offers substantial environmental advantages. Future research directions include optimizing the mix design for various applications and evaluating long-term performance in real-world structures. This project contributes to the broader effort in the construction industry to reduce greenhouse gas emissions and promote sustainability.**

I. INTRODUCTION

Geo-polymer concrete is a type of concrete that uses industrial by-products, such as fly ash and silica fume, to create a binding agent, eliminating the need for traditional cement. From an environmental perspective, there has been a significant increase in carbon dioxide (CO2) emissions due to factors such as energy consumption, transportation, and industrial activities. The concept of Geo-polymer chemistry was patented by the Geo-polymer Institute in 1979, laying the foundation for the development of novel binder materials. Subsequently, in 1983, Joseph Davidovits and James Sawyer introduced high strength Geo-polymer cement, which marked a significant advancement in the field.

The construction industry is one of the largest contributors to environmental degradation, particularly due to the production of Ordinary Portland Cement (OPC), which emits significant amounts of carbon dioxide (CO_2). In light of global climate change and increasing environmental concerns, alternative materials that reduce environmental impact are critically needed. Geo-polymer concrete (GPC) has emerged as a promising sustainable construction material. Synthesized from industrial by-products like fly ash and slag, and activated by alkaline solutions, GPC offers comparable or superior mechanical properties while drastically reducing carbon emissions. This paper explores the potential of Geo-polymer concrete as a sustainable replacement for OPC based concrete, focusing on its composition, mechanical behavior, and environmental impact.

One of the major advantages of GPC is its customizable nature. Engineers can tailor mix designs to achieve specific properties such as rapid setting, high early strength, or enhanced chemical resistance by varying the source materials, activator concentrations, and curing conditions. Geopolymer concrete demonstrates superior durability, with high resistance to acid attack, sulfate exposure, and chloride penetration. Its mechanical properties are also impressive, often matching or exceeding those of conventional concrete, with compressive strengths ranging from 30 to 70 MPa. Additionally, it exhibits lower drying shrinkage, improved creep resistance, and reduced permeability, which contribute to longer service life in aggressive environments.

II. LITERATURE REVIEW:

1. Performance Comparison of Fly Ash-Based Geopolymer Concrete with OPC Concrete (Darshan Jeevi Ghimire, Samrat Poudel, Nirmal Bard, 2024) -
This study aimed to evaluate the performance of geopolymer concrete made using 70% fly ash, 20% OPC (Ordinary Portland Cement), and 10% silica fume. The target compressive strength was set at 13 MPa, and the achieved compressive strength at 7 days was 15 MPa, demonstrating an improvement over the intended value. The authors compared the results with those of pure GPC made using only fly ash and silica fume. The study concluded that the addition of silica fume to GPC significantly enhances compressive strength and overall performance. Silica fume contributes to the densification of the microstructure and facilitates better bonding among constituents, leading to improved mechanical behavior. This finding underscores the potential of using ternary blends in GPC to achieve higher strength without depending entirely on OPC.

2. The Properties of Geopolymer Concrete by Partial Replacement of Cement with GGBS and Fly Ash (Mudigonda Rathna Chary, Kotha Hima Bindu, et al., 2024)
In this study, researchers cast and tested concrete cubes and cylinders using various ratios of fly ash (5–25%) and GGBS (10–30%). These specimens were evaluated for both compressive and tensile strength at 7, 14, and 28 days. The findings revealed that higher proportions of fly ash andGGBS contributed to improved strength up to an optimal level. Specifically, 20% fly ash and 25% GGBS yielded the best mechanical performance. However, the study also highlighted that excessive GGBS content (>30%) resulted in a slight decrease in strength, suggesting that optimal dosages must be maintained. Importantly, fly ash showed no adverse effects, making it a viable and sustainable binder material.

3. The Properties of Geopolymer Concrete by Partial Replacement of Cement with GGBS and Fly Ash (Mudigonda Rathna Chary, Kotha Hima Bindu, Jagadish Shrisaila Haranatti, Mohnika Samineni, Pasupuleti Pavani, Oleg Igorevich Rozhdestvenski, 2024)
This research further examined the mechanical behavior of geopolymer concrete when cement was partially replaced by combinations of fly ash and GGBS. Concrete cubes and cylinders were prepared with varying contents of fly ash (5–25%) and GGBS (10–30%). These specimens were tested for compressive and split tensile strength at 7, 14, and 28 days. The study confirmed that increasing both fly ash and GGBS content positively influences mechanical performance. The optimal mix again occurred at 20% fly ash and 25% GGBS, which provided maximum compressive and tensile strength values. These results validate the findings of previous research and reinforce the importance of identifying precise combinations for performance enhancement.

4. Partial Replacement of Cement with Fly Ash to Produce Environmentally Friendly Concrete (Ali Hassan, Muhammad Tariq Ali, Muhammad Zain Abdullah, Fahad Ali, Muhammad Arif, 2023)
In this investigation, geopolymer concrete cubes were cast and tested using different proportions of fly ash to assess compressive strength performance. The aim was to determine how replacing cement with fly ash affects the strength characteristics of GPC and its suitability as an environmentally friendly material. The results indicated that while incorporating fly ash into the concrete mix reduced the early-age strength compared to control specimens, the overall strength development improved with time. The study found that 20% fly ash produced higher strength compared to 30% fly ash, implying that there is a critical point beyond which increasing fly ash content may not yield benefits. This supports the idea that moderate fly ash content (around 20%) is optimal for achieving a balance between strength and sustainability.

5. Experimental Study on Geopolymer Concrete with Replacement of Fly Ash and GGBS Authors: Pravalika Panchalingala, I. Praveen Kumar Reddy Year: 2021 This experimental investigation focused

on studying the performance of geopolymer concrete made by replacing cement with varying proportions of fly ash and GGBS. The experimental tests included compressive strength, split tensile strength, flexural strength, acid resistance, sulphate resistance, and permeability. The goal was to evaluate both the mechanical and durability characteristics of GPC under different mix proportions and exposure conditions. The study revealed that a higher sodium silicate to sodium hydroxide ratio, combined with elevated curing temperatures, significantly enhances the compressive strength of GPC. Among all the mixes, the blend containing 30% fly ash and 70% GGBS exhibited the best overall performance, offering superior strength and resistance to chemical attack. Furthermore, this composition demonstrated better water resistance and environmental benefits than conventional concrete. These findings affirm that selecting an optimal ratio of binders and activators is essential to maximize the performance of geopolymer concrete in structural applications.

6. Experimental Studies on Partial Replacement of Cement with Fly Ash in Concrete Elements Author: K.V. Sabarish Year: 2017

This study aimed to assess the structural potential of geopolymer concrete by partially replacing OPC with fly ash. The research involved casting and testing concrete cubes with different proportions of fly ash to determine their compressive strength development. The results indicated that the partial replacement of cement with fly ash consistently improved the overall performance of the concrete. Specifically, the mixes with moderate fly ash content achieved satisfactory strength and durability parameters. However, excessive fly ash inclusion without optimization could compromise performance. This study supports the notion that fly ash serves as a viable substitute for cement in concrete production, especially in reducing carbon emissions and enhancing sustainability.

7. Replacement of Cement by Fly Ash in Concrete Authors: Jayanta Chakraborty, Sulagno Banerjee Year: 2016

This investigation focused on evaluating the impact of fly ash content on the compressive strength of geopolymer concrete. The experimental work involved casting and testing geopolymer concrete cubes with varying proportions of fly ash. The study found that increasing the percentage of fly ash in the mix led to a decrease in compressive strength. This result suggests that while fly ash can be used as a partial replacement for cement, there is a threshold beyond which strength properties begin to deteriorate. Therefore, careful proportioning and optimization of fly ash content are necessary to ensure that mechanical properties meet structural requirements. The findings emphasize that fly ash inclusion should be limited to levels where it can act synergistically with other binders to maintain or improve strength.

8. Comparison of GPC Fly Ash and OPC on Strength of Concrete Authors: Mohd Mustafa Al Bakin Abdullan, H. Kamorudin Year: 2013

This study compared the compressive strength of conventional OPC concrete and geopolymer concrete prepared using fly ash. In both cases, the same mixing and compaction method was employed to ensure consistency. The main distinction was that GPC used alkaline activator solutions (sodium hydroxide and sodium silicate) in place of water, which is traditionally used in OPC mixes. The findings showed that fly ash-based GPC achieved superior compressive strength, with results reaching up to 49.3 MPa at 28 days. This significant strength gain can be attributed to the efficient polymerization reaction facilitated by the alkaline activators, which leads to the formation of strong aluminosilicate gels. The study concluded that GPC not only matches but often outperforms OPC concrete in terms of strength, while also offering notable environmental advantages by utilizing industrial waste products such as fly ash.

9. On the Development of Fly Ash-Based Geopolymer Concrete Authors: Djwantoro Hardjito, Steenie E. Wallah, Dody M.J. Sumajow, B. Vijaya Rangan Year: 2004

This comprehensive study investigated the development of geopolymer concrete using fly ash as the primary binder. The experimental program included casting and testing cylindrical specimens (100×200 mm) and large column specimens (175×175×1500 mm) to assess their compressive strength under varying curing conditions. The study concluded that curing temperature plays a vital role in the strength development of GPC. Specifically, when the curing temperature was increased within a range of 30°C to 90°C, the compressive strength of the GPC also increased. This behavior was attributed to enhanced geopolymerization reactions at elevated temperatures, leading to a denser and stronger matrix. These findings underscore the importance of thermal curing in optimizing the mechanical performance of geopolymer concrete, especially during early strength development phases.

10. Optimum Mix for Geopolymer Concrete (GPC) Authors: M.I. Abdul Aleem, P.D. Arumairaj Year: 2004

This study aimed to determine the optimum mix proportions for producing geopolymer concrete with high compressive strength. The researchers carried out experiments on three cube specimens for each of four different mix combinations. The mixes were varied based on the percentage of fine and coarse aggregates, fly ash content, and alkaline activator proportions. The results demonstrated that an increase in the percentage of aggregate within the mix led to improved compressive strength. The optimum mix ratio was found to be 1:1.5:3.3 (fly ash: fine aggregate: coarse aggregate), activated using a solution of NaOH and Na_2SiO_3 with a fly ash to activator ratio of 0.35. This mix provided the best combination of workability, strength, and cost-effectiveness, offering a clear guideline for practical applications of GPC in structural work.

11. Fly Ash-Based Geopolymer Concrete Author: B.V. Rangan Year: 2003

Professor B.V. Rangan, a key figure in geopolymer concrete research, conducted this foundational study to explore the structural potential of low-calcium fly ash in producing GPC. The experimental setup included casting cylindrical specimens (100×200 mm), beams, and prisms (75×75×285 mm) to examine both compressive and flexural properties. The study concluded that low-calcium fly ash-based geopolymer concrete possesses excellent compressive strength, making it suitable for structural applications. The findings confirmed that the absence of calcium (unlike in Portland cement) did not hinder the strength performance of GPC, and the aluminosilicate polymer chains formed provided sufficient binding power and durability. This study strongly supported the use of fly ash as a sustainable and effective binder for structural concrete 12. Investigation Study on Geopolymer Concrete Authors: Vimalraj, Shaib Shabir, Vishal Singh Year: 2002 This study compared the compressive strength of conventional concrete and geopolymer concrete using cube specimens of 10×10×10 cm size. The aim was to examine how GPC performed under the same curing and testing conditions as traditional Ordinary Portland Cement (OPC) concrete. The results were as follows: • Conventional Concrete o 7 days: 18 MPa o 14 days: 29.25 MPa o 21 days: 40.5 MPa • Geopolymer Concrete o 7 days: 20 MPa o 14 days: 30 MPa o 21 days: 41 MPa These results indicate that geopolymer concrete consistently outperformed conventional concrete at every testing interval. The early strength gain in GPC was particularly notable, reflecting the efficient reaction of fly ash with the alkaline activator. This confirmed the viability of geopolymer concrete as a strong, fast-setting, and sustainable alternative to traditional cement-based concrete.

III. METHODOLOGY

- Preparation of alkaline activator solution-Mix the sodium hydroxide and sodium silicate.
- Measures and mix aggregates- Measure the required quantities of coarse and fine aggregate.
- Addition of fly ash-Add the measured amount of fly ash to the dry aggregates and mix them thoroughly.
- Addition of alkaline activated solution in fly ash aggregate & Addition of water.
- Casting of concrete mixture-Pour the concrete mixture in the molds or form-work and compact the concrete well to remove air voids.
- Curing of mixture.
- Demolding and post curing.

IV. EXPERIMENTAL WORK

- Perform compressive strength test on cube specimen.
- Cast 27 cubes of GPC with varying mix proportion, and 9 cubes of OPC of M30 Grade.
- 27 cubes with varying proportion of- 9 cubes (50% fly ash), 9 cubes (60% fly ash),9 cubes (70% fly ash).
- We will compare and analyze the strength of varying

V. RESULTS

An experimental study was carried out to evaluate the compressive strength of geopolymer concrete cubes using varying fly ash to cement ratios and alkaline activator mixing durations. The compressive strength was measured at two different curing periods—7 days and 28 days—to analyze strength development over time. The performance of these geopolymer mixes was also compared against standard OPC M30 concrete.

1. Fly Ash-Cement Ratio: 50-50 (Activator Mix Time: 24 Hours)

At a 1:1 fly ash to cement ratio with an alkaline activator mixed for 24 hours before casting, the average 7-day compressive strength was recorded at 4.61 MPa, while the 28-day strength improved to 11.06 MPa. This indicates a moderate strength gain over time, demonstrating that equal proportions of fly ash and cement, with a sufficient activator mixing period, can contribute to noticeable strength development. However, the initial 7-day strength is relatively low, which may limit early load-bearing applications.

2. Fly Ash-Cement Ratio: 60-40 (Activator Mix Time: 48 Hours)

For a mix ratio of 60% fly ash and 40% cement, with a prolonged alkaline activator mixing duration of 48 hours, the 7-day strength significantly increased to 7.76 MPa, although the 28-day strength was slightly 31 lower at 9.06 MPa. This unusual result suggests that while longer mixing with a higher fly ash proportion promotes early polymerization and strength gain, the long-term strength gain may plateau or even slightly decline. This could be due to improper setting behavior or oversaturation of activator solution affecting late-age hydration/geopolymerization.

3. Fly Ash-Cement Ratio: 70-30 (Activator Mix Time: 1 Hour)

This mix, with a higher percentage of fly ash (70%) and only 30% cement, was activated for a short period of 1 hour before use. The 7-day strength was 4.6 MPa, and the 28-day strength was 8.92 MPa. These values show that a shorter mix time leads to lower strength at both stages, especially in a fly ash-rich mix. The insufficient activator mixing time likely hindered proper geopolymerization, emphasizing the importance of adequate blend time for achieving desired performance.

4. OPC M30 Concrete (Reference Mix) As a benchmark, standard OPC M30 concrete was tested. The 7-day compressive strength was 28.31 MPa, and the 28-day strength reached 48.3 MPa. This confirms the superior strength performance of OPC-based concrete, especially in early strength development. It serves as a useful reference to gauge the performance gap between traditional concrete and geopolymer alternatives.

COMPRESSIVE STRENGTH TEST VALUES

Flyash-Cement Ratio	Alkaline activator mixed time	7 Days (Avg. Strength)	28 Days (Avg. Strength)
50-50	24hrs	4.61 Mpa	11.06Mpa
60-40	48hrs	7.76 Mpa	9.06Mpa
70-30	1hrs	4.6 Mpa	8.92Mpa
OPC M30	-	28.31 Mpa	48.3Mpa

COMPRESSIVE STRENGTH TEST VALUES

VI. CONCLUSION

The following conclusions can be drawn based on the test results:

The compressive strength test was conducted on geopolymer concrete cubes and OPC concrete cubes at 7 and 28 days. The average compressive strength of geopolymer concrete cubes was consistently lower than that of OPC concrete cubes across all curing periods. The expected improvement in strength due to the use of geopolymer binders (fly ash activator, etc.) was not achieved under the experimental conditions used in this study.

- The highest 7-day strength among geopolymer mixes was observed in the 60:40 fly ash-cement mix with 48 hours activator mixing (7.76 MPa), indicating that increased activator exposure enhances early strength.
- The 50:50 mix with 24-hour mixing achieved the highest 28-day strength among geopolymer samples

(11.06 MPa), suggesting that balance in mix proportion and adequate blending duration supports better longterm strength.

• Short activator mix durations (1 hour), especially in fly ash-dominant mixes (70:30), lead to reduced strength due to incomplete geopolymerization.

• Despite notable early strength development in some geopolymer mixes, all tested formulations showed significantly lower compressive strength than OPC M30 concrete, which surpassed 28 MPa at 7 days and 48 MPa at 28 days.

• The results indicate that the geopolymer concrete mix used in this study did not outperform OPC concrete in terms of compressive strength.

• The lower strength could be attributed to several factors such as:

• Improper alkali activator concentration or ratio ($NaOH/Na_2SiO_3$) • Inadequate curing method or curing temperature

• Poor mix proportioning

• Low reactivity of fly ash.

• Although geopolymer concrete is a promising sustainable alternative to OPC concrete, this study highlights the importance of optimizing mix design and curing conditions to achieve comparable or superior strength.

• Further investigation is needed to improve the strength characteristics of geopolymer concrete by:

o Adjusting the alkaline activator solution concentration.

o Using heat curing instead of ambient curing.

o Trying different source materials or combination of materials.

o Performing microstructural analysis for better understanding.

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