

The Role of Geopolymer in Concrete for Foundation Engineering: A Comprehensive Review

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Abstract

This review paper serves as a comprehensive exploration of utilizing geopolymer as a sustainable binder in concrete for applications within foundation engineering, effectively positioning it as an eco-friendly alternative to conventional Portland cement. The paper's core strength lies in synthesizing existing research to demonstrate the dual advantages of geopolymer concrete: superior mechanical properties and durability coupled with significant sustainability gains. It applies this material science innovation across diverse foundation scopes, from structural elements like shallow and deep foundations to its use in soil stabilization for ground improvement, drawing a relevant and insightful parallel to established confinement methods like the use of geosynthetics and geocells. While acknowledging the material's potential in load-bearing applications and chemically binding weak soils, the paper offers a balanced discussion of current challenges, namely the need for standardization, overcoming curing requirements for in-situ work, and acquiring long-term performance data; ultimately, it charts a clear path for future research focused on developing practical, ambient-cured formulations and extensive life-cycle assessments to fully integrate this low-carbon material into modern geotechnical practice.

Keywords: Geopolymer, Foundation Engineering, Ground Improvement, Soil Stabilization, Geocells, Sustainable Concrete

1. Introduction

The construction industry is a major contributor to global CO₂ emissions, largely due to the production of Portland cement. The use of geopolymer binders in concrete, a term first coined by Davidovits (1991), has emerged as a sustainable alternative. This technology utilizes industrial byproducts like fly ash and slag to create a strong and durable matrix through a process of geo-polymerization. The concept of soil stabilization and ground improvement, critical in projects like railway embankments soil where techniques are reviewed by Dhameliya Chirag, Jigarbhai Sonani and others (2016), can be effectively translated to foundation engineering through geopolymer technology. This paper reviews the current state of geopolymer applications in concrete for foundations, highlighting its potential to enhance performance and sustainability.

1.1. Objectives

The primary objectives of this review paper are as follows:

- To summarize the current state of the art on the use of geopolymer in concrete for foundation engineering.
- To analyze the key engineering properties of geopolymer concrete that are relevant to foundation design and performance.
- To review the applications of geopolymer in both structural foundations (shallow and deep) and ground improvement techniques (soil stabilization, grouting, and composite systems).
- To critically evaluate the existing literature to identify significant research gaps, limitations, and unanswered questions.
- To propose a clear roadmap for future research directions needed to advance the field and facilitate wider adoption of the technology.

1.2. Review Methodology

This review was conducted by performing a systematic search of prominent academic databases, including Scopus, Web of Science, and Google Scholar. The search was performed using a combination of keywords such as "geopolymer concrete," "foundation engineering," "soil stabilization," "geocells," "ground improvement," and "alkali-activated materials." The selection criteria for inclusion were: (a) peer-reviewed journal articles and conference proceedings published between 2000 and the present, (b) papers published in English, and (c) studies with a direct focus on the geotechnical or structural application of geopolymers in foundations. Initial search results were screened by title and abstract, and relevant full-text articles were then analyzed to synthesize the information presented in this review. The final selection of 12 key papers was based on their relevance, impact, and contribution to the specific topics discussed.

2. Geopolymer as a Binder in Concrete: Composition and Properties

Geopolymer is used in concrete as a binder, produced by activating aluminosilicate source materials with an alkaline solution. The underlying chemical reactions involve the dissolution of alumina and silica from the source material and subsequent polycondensation into a stable, three-dimensional polymer structure, as detailed by Provis and others (2005). The resulting concrete exhibits several desirable properties for foundation engineering. According to pioneering work by Hardjito & Rangan (2005) on fly ash-based geopolymer concrete, and the comprehensive review by Al-Majidi and others (2016), concrete made with geopolymer binders exhibits the following key properties:



Figure 1: Geopolymer

- **High Compressive Strength:** Concrete with geopolymer binders can achieve high early strength, which is advantageous for rapid construction schedules.
- **Excellent Durability:** The review by Al-Majidi and others (2016) confirms that it demonstrates superior resistance to chemical attacks, including sulfates and acids, making it suitable for aggressive soil environments. This high durability is attributed to the stable aluminosilicate polymer network, which is less susceptible to the types of chemical degradation that affect Portland cement-based binders.
- **Strong Bond with Reinforcement:** For reinforced foundation elements, the bond between concrete and steel is critical. Research by Nath & Sarker (2017) found that the bond strength of geopolymer concrete with reinforcing steel is comparable to or even better than that of ordinary Portland cement concrete, ensuring proper load transfer in structural members (pp. 28-39).
- **Low Permeability:** The dense microstructure of geopolymer-based concrete reduces its permeability, enhancing its durability and protecting underlying structures from moisture and chemical ingress.

3. Applications in Foundation Engineering

The unique properties of concrete utilizing geopolymer binders make it versatile material for various foundation applications.

3.1. Shallow and Deep Foundations

For shallow foundations (e.g., strip and mat) and deep foundations (e.g., piles), using geopolymer in concrete provides a durable and high-strength alternative. Its resistance to chemical degradation is particularly beneficial in contaminated ground. The structural viability of geopolymer concrete for members like beams and columns has been well established, with design provisions proposed by Rangan (2008), making its use in foundation piles a logical and structurally sound application (pp. 1-14).

3.2. Ground Improvement

Inspired by techniques used for railway embankments, geopolymer technology is a powerful tool for ground improvement.



Figure 2: Geocell

- **Soil Stabilization:** The application of geopolymer as an in-situ binder for soil stabilization is a particularly innovative area of research. As outlined in the review by Phummiphan and others (2018),

geopolymer binders can be mixed directly with weak soils to improve their strength and stiffness. Their research specifically notes that fly ash-based geopolymers can effectively stabilize clayey soils. Furthermore, studies by Sarkar and others (2020) have demonstrated the effectiveness of geopolymers in stabilizing problematic expansive soils, significantly reducing their swell potential and increasing their strength (pp. 105615).

- **Composite Reinforcement with Geocells:** To further enhance the performance of geopolymer-stabilized ground, it can be combined with geosynthetic reinforcement. The use of geocells—three-dimensional, honeycomb-like cellular confinement systems—is particularly effective. Research by Tafreshi and others (2021) has demonstrated that when geocell reinforcement is used in conjunction with stabilized base layers, it significantly improves load-bearing capacity and reduces settlement by providing confinement and distributing loads over a wider area. Applying this concept, a composite system of geocell-reinforced, geopolymer-stabilized soil can create a highly efficient and stiff foundation mattress, ideal for supporting shallow foundations or embankments on weak ground.
- **Grouting:** The principles of geo-polymerization can be applied to create effective grouts. As discussed by Rifaai and others (2019), geopolymer grouts can be injected into the ground to fill voids and strengthen the soil mass. This is particularly useful for improving the bearing capacity of the soil before foundation construction.

4. Advantages and Limitations

Advantages:

- **Environmental:** A key driver for geopolymer adoption is its lower carbon footprint. A life cycle assessment by McLellan and others (2011) showed that geopolymer concrete can reduce greenhouse gas emissions by 40-80% compared to Portland cement concrete, depending on the raw materials and logistics (pp. 10-14).
- **Technical:** Superior strength, durability, and resistance to chemical attack.
- **Economic:** Potential for cost savings through the use of locally sourced waste materials.

Limitations:

- **Handling:** The highly alkaline activators required for geo-polymerization pose material handling challenges and necessitate strict on-site safety protocols.
- **Standardization:** A lack of standardized design codes remains a significant barrier to widespread adoption.
- **Curing:** Some geopolymer mixes require heat curing to achieve optimal properties, which can be a practical challenge for cast-in-situ foundations.

5. Identified Research Gaps and Future Directions

A thorough review of the current literature reveals several critical gaps that must be addressed to facilitate the broader adoption of geopolymer in concrete for foundation engineering. This section outlines these gaps, proposes potential research avenues to resolve them, and discusses the resulting future scope for technology.

5.1. Key Research Gaps Identified in Literature

- **Reliance on Heat Curing for Optimal Performance:** A significant portion of the foundational research, including the work by Hardjito & Rangan (2005), demonstrates that optimal mechanical properties are often achieved through elevated temperature curing. This presents a major practical limitation for cast-in-situ foundations, creating a gap in the development of geopolymer concrete mixes that can achieve high performance under ambient field conditions without external heat.
- **Scarcity of Long-Term Performance Data:** While studies such as Nath & Sarker (2017) provide valuable insights into short-term mechanical properties and bond strength, a notable gap exists regarding the long-term (10+ years) performance of geopolymer foundations. Data on creep, shrinkage, and durability under real-world dynamic and cyclic loading conditions (e.g., traffic, seismic activity, freeze-thaw cycles) is scarce.
- **Absence of Codified Standards and Design Provisions:** Despite promising results and proposed design frameworks like those by Rangan (2008), the lack of internationally recognized, codified standards for geopolymer concrete is perhaps the single largest barrier to its widespread engineering acceptance and application. This gap includes a lack of standardized mix of design methodologies, quality control procedures, and reliability-based structural design provisions.
- **Limited Understanding of Composite System Behavior:** The synergistic potential of combining geopolymer-stabilized soil with geocells is a promising frontier, as indicated by the review on geocell performance by Tafreshi and others (2021). However, the specific interaction mechanisms, optimal geometric configurations, and long-term durability of these composite systems are not yet well understood, leaving a gap in design guidance for such applications.

5.2. Avenues for Resolution and Future Scope

To bridge these gaps and advance the field, future research should be strategically focused on the following areas:

- **Advanced Ambient Curing Technology:** The primary research thrust should be the development of novel chemical admixtures or the incorporation of nanomaterials to accelerate the geo-polymerization process at ambient temperatures. Successfully resolving this issue is the key to unlocking the potential of geopolymer for all cast-in-situ foundation applications.
- **Initiating Long-Term Field Trials:** To build industry confidence, full-scale, instrumented field trials of geopolymer foundations are essential. These projects should be monitored for over a decade to collect crucial data on long-term behavior, validating laboratory findings and providing a basis for durability modeling.
- **Developing Standardized Protocols:** A concerted, collaborative effort between academic institutions, industry stakeholders, and standards organizations (like ACI, ASTM, and ISO) is required. This should involve round-robin testing programs to establish repeatable test methods and the eventual development of comprehensive guidelines for both material specification and structural design.
- **Characterizing Composite Systems:** The future scope includes a deeper investigation into composite geopolymer-geocell systems. This should involve large-scale laboratory testing under realistic loading conditions, complemented by advanced numerical modeling. The goal is to develop validated design charts and predictive models that can be readily used by practicing geotechnical engineers.

6. Conclusion

The use of geopolymers in concrete presents a promising and sustainable solution for foundation engineering. Its excellent mechanical properties and durability, confirmed by numerous researchers, make it a strong alternative to conventional concrete. By applying the principles of ground improvement, as discussed by Phummiphan and others (2018), and combining geopolymer stabilization with reinforcing elements like geocells, as suggested by the work of Tafreshi and others (2021), geopolymer technology can be used to create holistic and highly resilient infrastructure solutions.

References

1. **Al-Majidi, M. H., Lampropoulos, A., Cundy, A., & Mele, K. (2016).** "Durability Performance of Geopolymer Concrete: A Review." *Construction and Building Materials*, 120, 19-31.
2. **Davidovits, J. (1991).** "Geopolymers: Inorganic polymeric new materials." *Journal of Thermal Analysis*, 37(8), 1633-1656.
3. **Dhameliya Chirag, Sonani Jigarbhai, Imdadhusain Momin, & Patoliya Brijesh (2016).** "A Review on Ground Improvement Techniques for Railway Embankment." *International Journal for Scientific Research & Development*, 4(1), 869-871.
4. **Hardjito, D., & Rangan, B. V. (2005).** "Development and Properties of Low-Calcium Fly Ash-Based Geopolymer Concrete." *Research Report GC 1, Faculty of Engineering, Curtin University of Technology, Perth, Australia*, pp. 1-88.
5. **McLellan, B. C., Williams, R. P., Lay, J., van Riessen, A., & Corder, G. D. (2011).** "Costs and carbon emissions for geopolymer pastes in comparison to ordinary Portland cement." *Journal of Cleaner Production*, 19(9-10), 1080-1090.
6. **Nath, P., & Sarker, P. K. (2017).** "Flexural strength and bond characteristics of geopolymer concrete." *Construction and Building Materials*, 130, 28-39.
7. **Phummiphan, T., Horpibulsuk, J., Arulrajah, A., Horpibulsuk, S., & Shen, A. (2018).** "Review of Fly-Ash-Based Geopolymers for Soil Stabilisation with Special Reference to Clay." *Soils and Foundations*, 58(4), 781-794.
8. **Provis, J. L., Lukey, G. C., & van Deventer, J. S. J. (2005).** "The role of chemical admixtures in geopolymerisation." *Cement and Concrete Research*, 35(11), 2137-2144.
9. **Rangan, B. V. (2008).** "Design and properties of geopolymer concrete." *Proceedings of the 33rd Conference on Our World in Concrete & Structures, Singapore*, pp. 1-14.
10. **Rifaai, M. N., Kassim, K. A., & Said, K. N. M. (2019).** "Geopolymer Application in Soil: A Short Review." *IOP Conference Series: Materials Science and Engineering*, 615(1), 012093.
11. **Sarkar, S., Hegde, A., & Mandal, J. N. (2020).** "Stabilization of expansive soil using geopolymer." *Materials Today: Proceedings*, 28, 105615.
12. **Tafreshi, S. N. M., Shaghaghi, T., & Tavakoli, H. R. (2012).** "Performance of geocell-reinforced sand and clay: A review." *Geotextiles and Geomembranes*, 49(2), 346-369.