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Review paper

APPLICATION OF SUSTAINABLE MATERIALS IN FOUNDATION ENGINEERING

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Abstract

Growing demand for sustainable construction methods has led to increased interest in using environmentally friendly materials in foundation engineering. This paper explores the potential applications, advantages, and challenges of using sustainable materials in foundation construction. The aim of the study is to compare sustainable alternative materials, such as recycled aggregates, geopolymers, and bio-binders, with traditional foundation materials.

The methodology includes a review of the literature and comparative analysis in the field of sustainable foundation materials. Their mechanical properties, durability, and environmental impact are analyzed. The results indicate that many sustainable materials exhibit superior performance in terms of load-bearing capacity and longevity, while reducing carbon footprint and natural resource consumption.

The study highlights the need for further research, standardization, and regulatory support to enable wider adoption of these materials in foundation engineering. By integrating these materials into geotechnical practice, the construction industry can contribute to the development of sustainable and resilient infrastructure.

Key words: *Sustainable materials, foundation construction, recycled aggregates, geopolymers, environmental impact*

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1. SUSTAINABLE BUILDING MATERIALS: IMPACTS ON PERFORMANCE, HEALTH, AND ENVIRONMENTAL OUTCOMES

The growing environmental consciousness of recent years underscores the imperative to design and construct buildings that prioritize ecological integrity and resource efficiency. Rapid population growth and escalating demands for housing necessitate careful planning to ensure that basic settlement needs are met while preserving natural systems and safeguarding resources for future generations. In this context, community-driven models that integrate green construction principles with affordable housing solutions have emerged as a vital strategy for mitigating the impacts of climate change. Such approaches emphasize energy conservation, the reuse of rainwater, the optimization of natural light and ventilation, and the use of locally sourced, renewable materials that minimize embodied energy, reduce pollution, and pose fewer health risks. By adopting circular design frameworks that interlink energy, water, and material flows, these projects not only enhance environmental performance but also raise occupants' awareness of sustainable living practices [1].

Concrete alternatives are emerging to address the high carbon footprint of ordinary Portland cement. Recycled aggregate concrete replaces virgin coarse aggregate with crushed demolition waste, maintaining comparable compressive strengths while diverting material from landfills [2]. Fly ash and slag-based binders leverage industrial by-products to substitute up to 50% of cement clinker, yielding mixtures with lower embodied CO_2 and enhanced long-term durability [2]. Geopolymer concretes synthesized from aluminosilicate precursors offer an additional pathway, demonstrating up to 80% lower life-cycle emissions when activated with alkali solutions derived from industrial residues [3].

Interior finishes and non-structural elements play a vital role in occupant health and well-being. Natural clay and lime-based plasters regulate indoor humidity through hygroscopic buffering, inhibit mold growth, and contain no synthetic binders or plasticizers [4]. Low-VOC paints and coatings often water-borne and derived from plant oils or mineral fillers minimize off-gassing of formaldehyde and other harmful compounds, improving cognitive performance and reducing sick-building symptoms by up to 50% in green-certified offices [5]. Flooring options such as cork and reclaimed hardwood not only close material loops but also provide acoustic damping and thermal comfort underfoot, further enhancing the indoor environment without reliance on petrochemical-derived plastics [6].

2. FUNDAMENTAL PRINCIPLES OF FOUNDATION ENGINEERING: ANALYSIS OF TRADITIONAL AND MODERN FOUNDATION SYSTEMS

Foundation engineering is a critical sub-discipline of civil and geotechnical engineering that deals with the design and construction of structures that safely transfer loads to the ground. At its core, the design of a foundation involves an understanding of soil behavior, load distribution, and structural interaction with the subsurface environment [7]. Its primary objective is to ensure that buildings, bridges, and other civil works remain stable and serviceable throughout their intended lifespan. The fundamental considerations in foundation engineering include load magnitude and distribution, soil and rock properties, groundwater conditions, and the interaction between the structure and the supporting ground [8]. Over the centuries, foundation systems have evolved from traditional methods-such as isolated pad foundations, raft foundations, and timber piles-to modern systems that incorporate advanced materials, prefabrication techniques, and innovative installation methods like helical and screw piles.

Well-designed foundation must account for potential settlement both immediate and time-dependent (consolidation). Settlement analysis requires understanding the soil's compressibility and the rate at which pore water dissipates under applied loads. Engineers also consider lateral earth pressures when designing retaining structures or foundations adjacent to steep slopes. In summary, the fundamental principles of foundation engineering revolve around load distribution, effective stress analysis, and the prediction of soil–structure interaction under various environmental and loading conditions.

2.1. Traditional Foundation Systems

Traditional foundation systems have been developed over centuries and are primarily based on empirical observations and classical mechanics. Common traditional systems include spread footings (or isolated pad foundations), strip foundations (Figure 1), and raft (or mat) foundations. For example, spread footings are designed to distribute the load over a large area to avoid overstressing the underlying soil [8]. These foundations typically involve the use of reinforced concrete poured in situ, sometimes combined with masonry elements in older constructions.

Another well-established traditional method is the use of timber piles, which were historically driven into the ground to support structures in soft or wet soils [9]. In ancient construction practices, stone pedestals and trench foundations were used to level structures and provide a stable support base. Despite their historical significance, many traditional systems have limitations. Their performance is often affected by soil heterogeneity, variable workmanship, and, in some cases, the susceptibility of materials (e.g. timber) to decay or deterioration over time.

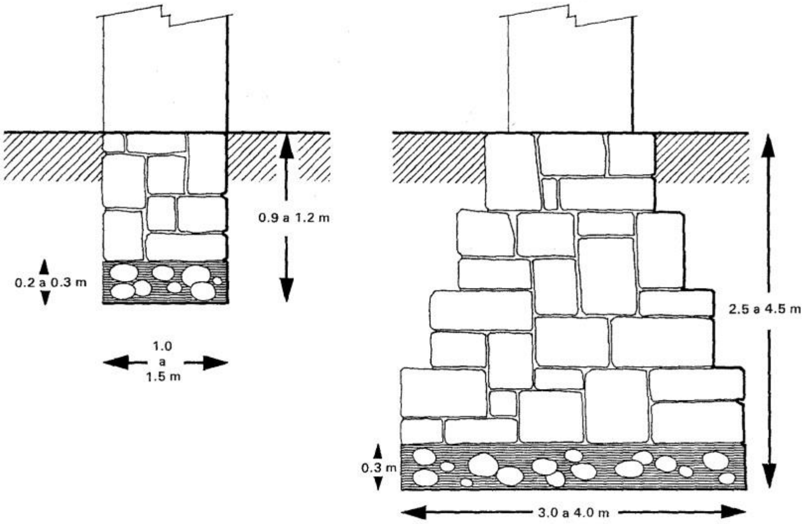


Figure 1. Strip foundations in Ancient Greek architecture [9]

Traditional systems generally rely on local materials and labor-intensive construction techniques. Although they have a proven track record, these methods sometimes lack the precision required to control differential settlements and may not adequately address modern seismic or dynamic load requirements [7]. However, the simplicity and robustness of traditional systems continue to influence contemporary practices, particularly in regions where modern construction methods are not feasible due to economic or resource constraints.

2.2. Modern Foundation Systems

Modern foundation systems have emerged as a result of advances in materials science, computational modeling, and construction technology. One of the key features of modern foundations is the incorporation of prefabricated components and specialized piles, such as helical and screw piles, which are manufactured offsite under controlled conditions [10]. These systems benefit from high precision and quality control, which contribute to improved performance in terms of load distribution and resistance to environmental factors such as soil expansion and seismic forces.

Modern methods also make extensive use of computer-aided design (CAD) and finite element analysis (FEA) to predict the interaction between the foundation and the soil accurately. For instance, advanced modeling techniques allow engineers to simulate time-dependent soil behavior and the effects of moisture fluctuations on expansive clays, leading to more effective mitigation strategies [11]. Furthermore, modern foundations often incorporate composite materials, including high-performance concrete and steel reinforcement, to enhance durability and reduce settlement under variable loading conditions. An example of such a system is the foundation of the Burj Khalifa, which demonstrates the integration of high-performance materials and advanced analysis techniques (Figure 2).

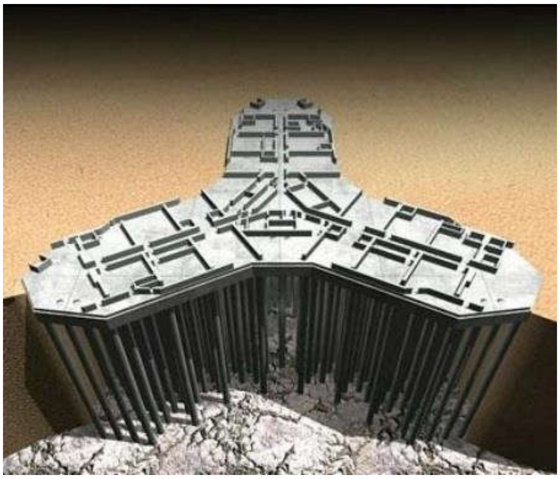


Figure 2. Burj Khalifa Tower Foundation system [12]

An important aspect of modern foundation systems is sustainability. With an increasing focus on minimizing the environmental impact of construction, modern designs aim to reduce material wastage, improve energy efficiency, and lower the overall carbon footprint. Innovations such as 3D printed concrete elements and the use of recycled materials exemplify the move towards more sustainable construction practices, while also providing economic advantages through reduced construction time and labor costs.

2.3. Comparative Analysis

The evolution from traditional to modern foundation systems reflects both technological advancements and a growing emphasis on precision, performance, and sustainability in foundation engineering. While traditional foundations have served as the backbone of construction for centuries, their limitations in terms of quality control and adaptability to diverse soil conditions are becoming increasingly evident. Modern foundation systems, underpinned by advanced modeling techniques and innovative materials, offer improved performance, enhanced durability, and a lower environmental impact. The integration of numerical analysis tools and sustainable practices in modern foundation design not only enhances the safety and serviceability of structures but also contributes to the efficient use of resources-a critical consideration in today's construction landscape.

3. SUSTAINABLE MATERIALS IN FOUNDATION ENGINEERING

Sustainable development has become a critical consideration in the engineering profession, necessitating that fundamental infrastructure be developed with minimal environmental degradation and long-term economic, social, and environmental viability in mind. In foundation engineering, the selection and use of sustainable materials is a key component in achieving these objectives. Sustainable materials not only reduce the overall environmental footprint of construction but also enhance the resilience and durability of geotechnical systems in the face of evolving climate and socio-economic challenges.

The overarching objective of sustainable engineering is to integrate technical systems harmoniously into both natural and human-made environments, without impairing the operational integrity of either domain. This integration must be achieved across multiple scales: local, regional, and global to ensure that engineered solutions contribute positively to environmental stewardship, economic viability, social equity, and sound design principles [13].

Accordingly, sustainability in engineering can be conceptualized as a dynamic equilibrium among four interdependent pillars: engineering design, economy, environment, and equity often referred to as the "Four E's" of sustainable development (Figure 3).

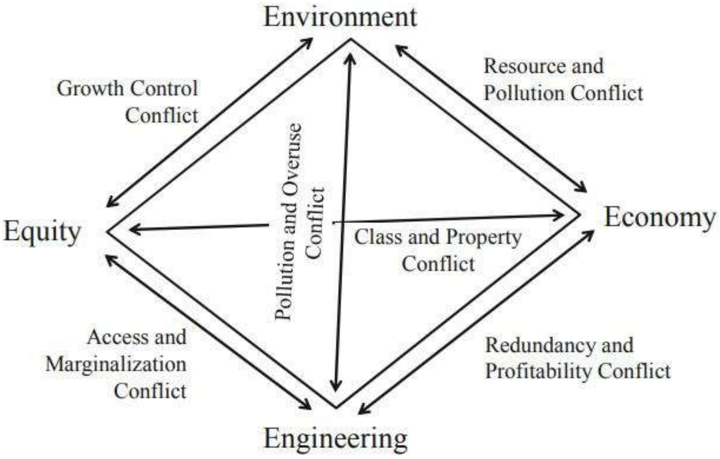


Figure 3. The four E's of sustainability in engineering projects [13]

In line with the four E's framework (engineering design, economy, environment, and equity) several sustainability objectives can be integrated into geotechnical engineering practice. These include early involvement of all stakeholders during the planning phase to establish a shared understanding of sustainability goals, such as pollution reduction and the use of environmentally friendly alternative materials [13].

The integration of sustainable materials into foundation engineering also requires overcoming several technical and logistical challenges. One primary concern is ensuring that substitute materials meet established performance criteria, particularly regarding strength, deformation behavior, and resistance to environmental degradation.

3.1. Recycled Aggregates

The mechanical behavior of recycled aggregates when used in foundation engineering has been the subject of various investigations. Researchers have demonstrated that, with proper processing and quality control, recycled aggregates (Figure 4) can exhibit compressive strengths and stiffness values comparable to those of conventional materials. Nonetheless, challenges remain in ensuring consistent material properties due to the heterogeneous nature of recycled components. The variability inherent in recycled aggregates necessitates rigorous testing protocols and the development of standardized criteria to ensure that they meet the structural demands imposed by building foundations [14]. Moreover, several studies have highlighted the importance of pre-treatment processes, such as washing and sorting, to remove impurities that could compromise the aggregate's performance. These pre-treatment methods not only enhance the mechanical properties of the recycled material but also extend its service life within geotechnical applications.

Figure 4. Recycled aggregate [15]

The foundation of a building is fundamentally concerned with soil–structure interaction, where the chosen materials must provide adequate load-bearing capacity and stiffness while maintaining long-term durability. When recycled aggregates are employed in such settings, they must be evaluated against performance criteria that include settlement behavior, resistance to dynamic loading, and durability under environmental stressors. Recent experimental and numerical studies have provided encouraging results, indicating that recycled aggregates can be successfully integrated into foundation systems with proper design adjustments. In particular, the use of recycled aggregates in sub-base layers or as a component of blended granular mixtures has shown to mitigate issues related to variability and enhance overall performance [14].

The adoption of recycled aggregates in the foundation of buildings signifies a noteworthy step toward the realization of sustainable construction practices. By integrating recycled aggregates, the construction sector can simultaneously reduce its environmental impact and meet the performance requirements of modern engineering. As the body of research expands, further refinements in material processing and design strategies will undoubtedly contribute to overcoming current limitations, thereby ensuring that recycled aggregates continue to evolve as a reliable, sustainable material option in the foundational engineering domain [16].

3.2. Geopolymers

Geopolymers have emerged as a sustainable alternative to conventional cementitious binders, offering significant potential for foundation engineering applications. Their synthesis involves the alkaline activation of aluminosilicate precursors often industrial by products such as fly ash or slag to form a hardened binder with high compressive strength, chemical stability, and resistance to thermal and acid attacks. These characteristics make geopolymeric materials particularly attractive in building foundations, where durability and long-term performance are critical under various loading and environmental conditions [17]. In addition to their advantageous mechanical properties, geopolymers present a lower embodied energy and substantially reduced carbon dioxide emissions relative to traditional ordinary Portland cement, thereby contributing to a more sustainable construction paradigm. The microstructure of cement lime stabilised soils is typically dominated by flaky calcium-silicate-hydrate (CSH) crystals, which form a cementitious paste that coats and binds individual soil grains, fills pore spaces and thereby enhances interparticle bond strength (Figure 5. a). In sulfidic environments, the same treatment often yields expansive ettringite crystals within interparticle voids, leading to volumetric swelling and increased porosity (Figure 5. b) [18]. In foundation applications, the implementation of geopolymeric binders offers several technical benefits.

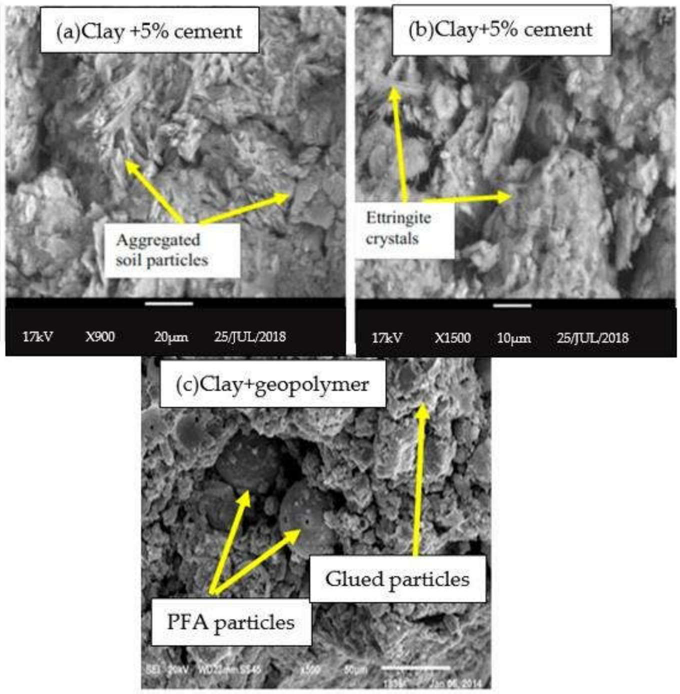


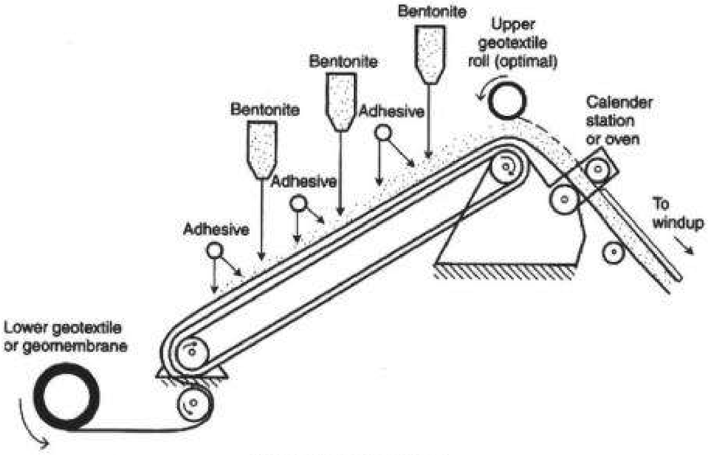
Figure 5. SEM of Stabilised Clays (a) 5% Cement-stabilised Clay (b) 5% Cement-stabilised Clays Showing Ettringite Crystals (c) PFA Stabilised Clay [18]

Their rapid strength development is conducive to early load-bearing capacity, a critical factor in foundation construction while their refined pore structure enhances resistance to the ingress of deleterious agents such as chloride ions and water, thereby mitigating durability concerns. However, the heterogeneous nature of the precursor materials demands robust quality control measures and standardized protocols to ensure consistency in mechanical performance and long-term stability. Research indicates that optimizing the mix design and curing regime is essential to harness the full potential of geopolymers in structural contexts, particularly under cyclic and sustained loads commonly experienced by building foundations [19]. Ongoing studies are focused on bridging the gap between laboratory-scale performance and field applications, ensuring that geopolymers can reliably replace conventional materials without compromising structural integrity. The evolution of geopolymer technology thus aligns closely with global initiatives aimed at reducing the carbon footprint of the construction industry, while simultaneously enhancing the resilience and service life of foundational systems. As geopolymers continue to demonstrate promising results, their integration into foundation engineering is poised to redefine sustainable practices in the built environment.

3.3. Geosynthetics

The integration of geosynthetics into foundation engineering has significantly transformed traditional construction practices by enhancing soil stability, reducing settlement, and improving load distribution. Recent studies have demonstrated that geosynthetic materials, such as geotextiles, geogrids, and geomembranes, provide multiple functions including reinforcement, separation, filtration, and drainage, improving the performance of foundation systems. Figure 6 illustrates two common manufacturing methods of geosynthetic clay liners (GCLs), which are widely used for reinforcement and hydraulic barrier applications in foundation engineering. Their high tensile strength and resistance to chemical degradation enable the effective reinforcement of weak soils and mitigation of differential settlement, resulting in enhanced soil-structure interaction under varying environmental conditions [20].

The use of geosynthetics contributes to sustainable construction practices by reducing the reliance on conventional materials, which in turn lowers the overall environmental impact. Despite promising laboratory and field outcomes, the successful application of these materials requires standardized design methodologies, robust quality control, and ongoing research to ensure long-term durability and performance [21]. Collaborative efforts among researchers, industry professionals, and regulatory agencies continue to refine installation techniques and material properties, further solidifying the role of geosynthetics as a cost-effective and environmentally responsible solution in modern foundation engineering.



(a) Adhesive mixed with clay

(b) Needle punched or stitch bonded through clay

Figure 6. Methods of manufacturing different types of geosynthetic clay liners [20]

3.4. Bio-Based Materials and Mycelium Composites

Bio-based materials, particularly mycelium composites, are increasingly recognized as innovative alternatives in foundation engineering. Derived from renewable resources—such as lignocellulosic substrates colonized by fungal mycelium—these materials boast lower embodied energy and reduced carbon emissions compared to conventional cementitious systems. Early research indicates that, with optimized processing, mycelium composites can achieve suitable compressive strength and thermal insulation properties for certain foundation applications [22]. However, challenges including moisture sensitivity, long-term durability, and variability in mechanical performance persist, necessitating rigorous quality control and standardized testing protocols to ensure their reliability under the sustained loads typical in building foundations.

The incorporation of bio-based materials into foundations supports sustainable construction by reducing reliance on non-renewable resources and promoting the circular economy through waste minimization and reuse of organic by-products [23]. Laboratory evaluations have provided promising insights into the potential of these materials as environmentally friendly alternatives in foundation design, though further interdisciplinary research is required to refine material formulations and processing techniques. The integration of mycelium composites not only contributes to the reduction of environmental impact but also offers economic benefits by potentially lowering lifecycle costs associated with maintenance and material replacement. As ongoing collaboration among material scientists, structural engineers, and sustainability experts advances this field, bio-based materials are poised to emerge as a viable, cost-effective solution for enhancing the sustainability of building foundations [24].

3.5. Case Studies and Applications in Foundation Engineering

The application of sustainable materials in foundation engineering is becoming increasingly important, and through specific case studies, it is possible to observe their actual performance, advantages, and challenges in practice.

3.5.1. Sustainable Pile Foundations

Recent studies have demonstrated that sustainable materials can be successfully integrated into foundation systems, particularly in pile foundations. A quantitative sustainability indicator system has been developed for comparing resource consumption and environmental impacts between drilled shafts and driven piles. The life cycle assessments (LCA) performed on these systems indicate that by incorporating sustainable materials—such as recycled aggregates and supplementary cementitious materials—the environmental footprint of pile foundations can be substantially reduced while maintaining or even exceeding technical performance requirements [25]. For instance, using fly ash as a partial substitute has shown to decrease both the embodied energy and CO_2 emissions associated with the concrete used in pile foundations.

3.5.2. Geopolymer Foundations

A case study from a recent project in Europe evaluated the performance of geopolymer-based concrete in the construction of a deep foundation system. The project used a geopolymer mix with a high replacement level of Portland cement by fly ash and slag. Field monitoring indicated that the geopolymer foundations exhibited comparable load-bearing behavior to traditional concrete foundations, while the LCA results highlighted a reduction of up to 40% in CO_2 emissions [3]. The increased durability under aggressive environmental conditions further underscored the long-term benefits of adopting geopolymer systems in foundation engineering.

3.5.3. Economic and Technical Benefits

Beyond the environmental advantages, sustainable materials can offer significant economic benefits. A reduction in raw material costs due to the use of industrial by-products, coupled with a potential decrease in lifecycle maintenance costs, can improve the overall cost efficiency of foundation projects. Additionally, sustainable materials tend to exhibit enhanced durability, reduced permeability, and better chemical resistance—factors that contribute to extended service life and lower repair frequencies. These benefits are particularly important in infrastructure projects where long-term performance and reliability are critical.

4. CONCLUDING REMARKS

This study demonstrates the growing relevance and applicability of sustainable materials in foundation engineering. Through an in-depth analysis of recycled aggregates, geopolymers, geosynthetics, and bio-based composites, it is evident that these materials can provide technical performance on par with or superior to conventional solutions, while significantly reducing environmental impact. Their potential to reduce embodied carbon, enhance durability, and lower long-term maintenance demands makes them a compelling alternative in the context of sustainable infrastructure development.

However, the transition toward widespread use of sustainable materials in foundation systems is not without challenges. Variability in material properties, lack of standardization, and uncertainties in long-term performance under complex loading and environmental conditions remain key barriers. Rigorous testing protocols, enhanced quality control, and context-specific design methodologies are essential to overcome these limitations.

Future advancements in material science, coupled with regulatory incentives and interdisciplinary collaboration, are likely to accelerate the adoption of sustainable alternatives in geotechnical practice. By integrating these materials into design and construction strategies, the foundation engineering community can play a pivotal role in addressing global sustainability targets, thereby fostering infrastructure that is not only structurally sound but also environmentally responsible and economically viable.

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