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Geopolymers: An Eco-Friendly Approach to Enhancing the Stability of Earthen Constructions

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Abstract. Earthen constructions, characterized by their historical longevity and adaptability to various environments, constitute an essential part of the global architectural heritage. These structures offer environmental advantages by utilizing local resources, but they also face challenges such as weather sensitivity, vulnerability to earthquakes, and degradation over time. Preserving these constructions while meeting modern sustainability standards poses a crucial challenge. In this context, geopolymers emerge as innovative solutions for stabilizing earthen constructions. A sustainable alternative is provided by geopolymers, which are composed of fly ash and ground granulated blast furnace slag to enhance soil cohesion and strength. This review article aims to provide an insightful perspective on compression tests specific to various types of geopolymers. The objective is to guide the choice of the method for stabilizing earthen constructions based on available resources.

Introduction

The pressure on the demand for construction materials is significantly intensified by population growth. This can lead to deforestation, contributing to the reduction of natural carbon sinks and increased exploitation of fossil fuels. This phenomenon is one of the major issues causing greenhouse gas emissions, thereby driving climate change. To address these challenges, it is crucial to promote sustainable construction practices, such as earth construction.

In 1982, earthen construction was one of the most widely used building materials for houses worldwide, with approximately one-third of the global population residing in such dwellings [1]. This practice has seen a decline in prevalence, and it is estimated that almost 25% of the world's population lives in houses made of earthen material. Recyclability, durability, high thermal capacity, and cost-effectiveness during construction are all advantages that rammed earth construction offers [2] . This building material is an intriguing choice due to its many benefits. Nonetheless, it is crucial to reinforce and stabilize it to increase its resistance to external forces.

The construction technique of rammed earth relies on the level of soil compaction, whether done manually or mechanically [3]. Generally, it can be utilized either by pouring it directly into a formwork to build walls or by molding bricks. The latter approach involves creating blocks out of soil, water, and a binder, assembling them in molds, and then compressing them with a hydraulic press.

An exploration of various earth construction methods, such as rammed earth, and earth block construction, reveals the crucial role of stabilization in ensuring the durability and strength of these structures. Chemical soil stabilization emerges as a promising technique for enhancing structural safety and reducing repair and rehabilitation costs. Cement and lime, among the most common chemical binding agents for stabilizing expansive soils [4], carry a negative environmental impact due to their energy-intensive manufacturing processes and greenhouse gas emissions, contributing to global warming [5].

Scientific research is increasingly turning to new, innovative stabilization pathways. Among these alternatives are:

Stabilization using geopolymers: An innovative approach to consolidating earth structures involves the use of geopolymers. Geopolymers are inorganic materials, typically aluminosilicate materials, synthesized from an activator solution and solid aluminosilicate materials. Geopolymers are characterized by their long-range covalent networks, which impart stabilization properties that improve the mechanical strength of earth constructions while minimizing the impact on the ecosystem

Understanding Geopolymers: The Science of Geopolymerization

The term geopolymer was originally named and developed by Professor Joseph Davidovits. He defined them as new materials for coatings and adhesives, new binders for fibrous composites, waste encapsulation and a new cement for concrete [6].

The semi-crystalline or amorphous form in a three-dimensional network is a key feature of geopolymers, which are green inorganic polymers made of aluminosilicate constituents and are characterized accordingly [7].

The term "geopolymer" was not used until 1978 by French chemist Joseph Davidovits. The term refers both to the inorganic nature of these materials and their polymer-like structure.

At the outset, the exploration into geopolymers concentrated on employing natural source materials like kaolin, calcined clays, silica fume and metakaolin. In more recent times, investigations have expanded to include industrial byproducts, for instance, fly ash [8–10], clay-based slag [11,12],Enhancing its sustainability with regard to environmental aspects, accessibility, and economic influence is a priority.

Geopolymers are characterized by their general chemical formula: M^+ n{$(SiO_2)_z$, AlO_2}n, w H_2O with n the degree of polymerization, z the Si/Al molar ratio and M^+ the monovalent cation. The formation of geopolymers is the result of polycondensation and geopolymerization reactions, in which SiO_4 and AlO_4 tetrahedra form a three-dimensional network. The alkali cation M^+ ensures neutrality by compensating for the charge deficit created by the substitution of an Si^{4+} cation by an Al^{3+} cation.

Geopolymer composites: a sustainable solution for soil stabilization:

Alkali-activated materials (AAM), also known as inorganic polymer materials called geopolymers, can be synthesized from natural materials and waste through an alkaline or acidic activation reaction.The advantages of Geopolymers, which are fire-resistant, chemical corrosion resistant, have high mechanical strength, and excellent durability[13,14].Optimal performance and low carbon dioxide emissions have been the main reasons geopolymer materials have been considered as substitutes for Ordinary Portland Cement (OPC) in the early 1980s.

Fly ash geopolymer:

As per the investigation conducted by R.K. Preethi et al. [15], investigates the durability of alkali-activated compressed earth cylindrical samples, which include a 30% clay fraction and 20% kaolin clay, incorporating varying levels of fly ash. The findings indicate that increasing the fly ash content enhances moisture resistance across specimens, independent of the alkali activator's molar concentration. As the fly ash content goes up from 5 to 15%, the compressive strength of natural soil samples increases by roughly 60%. With a clay content of 30%, fly ash percentage of 15%, and 12 M NaOH, the highest recorded strength is around 4 MPa. Additionally, strength improves with increasing molarity, from 8 molars to 12 molars. For samples with 20% kaolin, a nearly twofold increase in wet strength is achieved by increasing the fly ash content from 4 to 15%, which reaches around 3.15 MPa. In addition, as the molarity increases from 8 to 12 M, strength increases by about 70% with 4% fly ash and 60% with 15% fly ash.

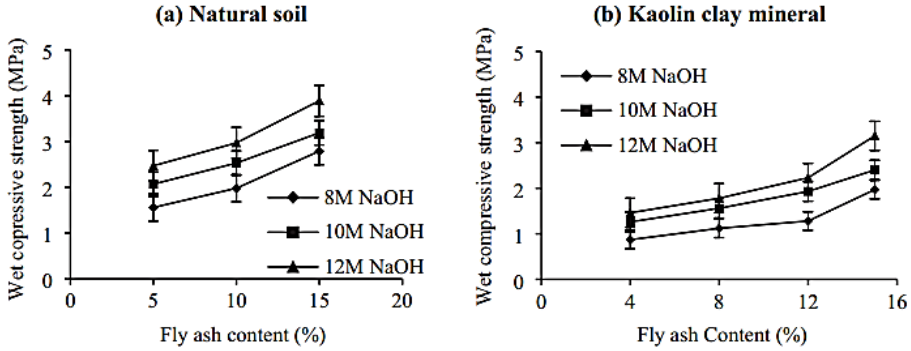

Fig. 2. *Compressed earth specimens made with (a) natural soil or (b) Kaolin clay mineral exhibit differences in strength based on the fly ash content.*

Hany et al.[3] investigated the impact of adding fly ash (FA) and an alkaline solution (AS) on the strength of raw earth bricks. They observed a significant early-age (7-day) strength increase in bricks with FA. Additionally, the long-term (28-day) strength of dried bricks was satisfactory. However, bricks exposed to humid conditions experienced a decrease in long-term strength due to leaching of the alkaline solution. In conclusion, FA addition strengthens raw earth bricks, but its effectiveness depends on environmental conditions.

Ground granulated blast furnace slag (GGBS)-based geopolymer:
Ground Granulated Blast Furnace Slag (GGBS) is a by-product of steel production. It is a granular, glassy material that is rich in silica and aluminates.

Mostafa Zamanian et al. [16] assess stabilization effectiveness primarily through the strength of cementitious bonds, geopolymerization, and suction stress. Curing conditions, especially in hot and dry environments, impact the quality of bonds, with GGBFS-based geopolymer samples showing enhanced compressive strength due to inter-particle geopolymer bonds. Cold curing conditions are discouraging. Suction stress from water evaporation also influences compression strength. GGBFS-based geopolymer samples are more sensitive to curing conditions compared to stabilized Ordinary Portland Cement (OPC) samples. Binder content significantly affects improvement efficiency, varying with curing conditions. In hot and dry conditions, incorporating WTTF fibers enhances UCS, but in moderate and cold conditions, it slightly decreases. To summarize, stabilized samples' strength is affected by binder type, curing conditions, binder content, and fiber incorporation.

For A. Neha VIVEK and al.[17] the compressive strength of wet-tested rammed earth cylinders after 28 days was examined, revealing a more than 100% increase with the addition of cement and Ground Granulated Blast Furnace Slag (GGBS). A significant improvement in wet compressive strength is observed with an increased GGBS percentage, reaching 3.51 MPa from an initial 0.83 MPa. The highest wet compressive strength (3.51 MPa) is achieved with a mix containing 12.4% clay and 20% GGBS. This improvement is attributed to a denser soil matrix due to hydration and slow pozzolanic reactions between soil compounds and GGBS. The initial tangent modulus (ITM) for GGBS specimens ranges from 1770 MPa to 3573 MPa, increasing by 74% with a higher GGBS percentage. Failure modes during compression tests correspond to a brittle type of failure.

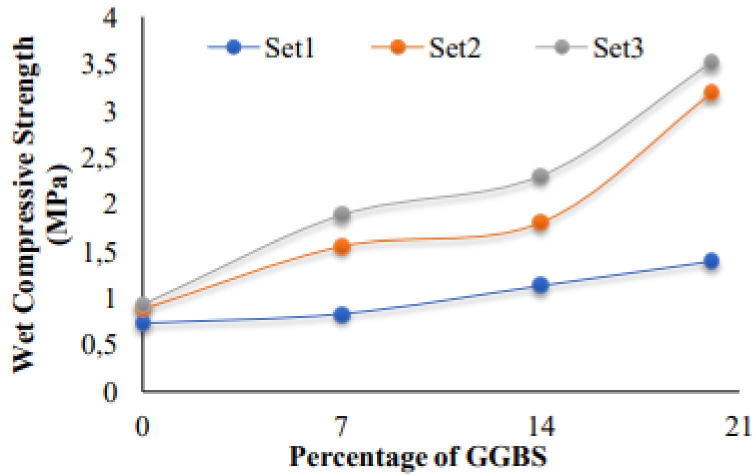

Fig. 3. *Impact of GGBS content on wet compressive strength*

Pozzolana geopolymer:

Pozzolana is a natural volcanic rock that has been utilized in construction for centuries. Abundant in silica and aluminates, it has the ability to react with hydrated lime to create cementitious compounds. These cementitious compounds are accountable for the strength and durability properties of pozzolana.

Rolande Aurélie Tchouateu Kamwa et al. [18] exhibit the outcomes of compression strength tests conducted on Compressed Earth Blocks (CEB) that were stabilized with a geopolymer binder that was activated with phosphoric acid-activated pozzolana in both dry and wet conditions. The mass ratio of phosphoric acid solution to pozzolana was kept constant at 0.8. Overall, the addition of stabilizers is the main factor that influences the strength of geopolymer samples. At 25°C, compressive strength in dry conditions gradually increases with the addition of stabilizer, reaching 20.6 MPa for a 20% by weight stabilizer content. At 70°C, the strength reaches its maximum at 42.8 MPa with a 15% by weight stabilizer content, decreasing to 36.9 MPa with additional stabilizer at 20% by weight. Cohesion between the stabilizer products and unreacted particles influences strength, generating materials with significant mechanical properties. Geopolymeric phosphatic gels derived from pozzolana ensure the stabilization of clayey soils based on CEB. At 70°C, the threshold temperature for the geopolymerization of pozzolanas according to [19], a significant mechanical gain is achieved due to the catalytic action of the polymerization/polycondensation reaction. In an acidic environment, the intra-stabilization of solid cement in CEB is evidenced by its compressive strength at both 25°C (9.7 MPa) and 70°C (10.2 MPa). The weight stabilizer's 20% decrease in strength indicates that a weight stabilization of 15% is sufficient for effective stabilization. The trend for compressive strength in wet conditions is similar to that of dry strength, with a significant decrease of 43.7% at 25°C and 43.8% at 70°C, in accordance with previous studies on phosphatic geopolymer binders. At 70°C, 15% pozzolana by weight seems to be the best option for stabilizing CEB, with a stronger strength than that of CEB stabilized by OPC and other geopolymer binders. These CEB can be used as construction bricks in areas subjected to significant weathering, while others are suitable as load-bearing masonry elements.

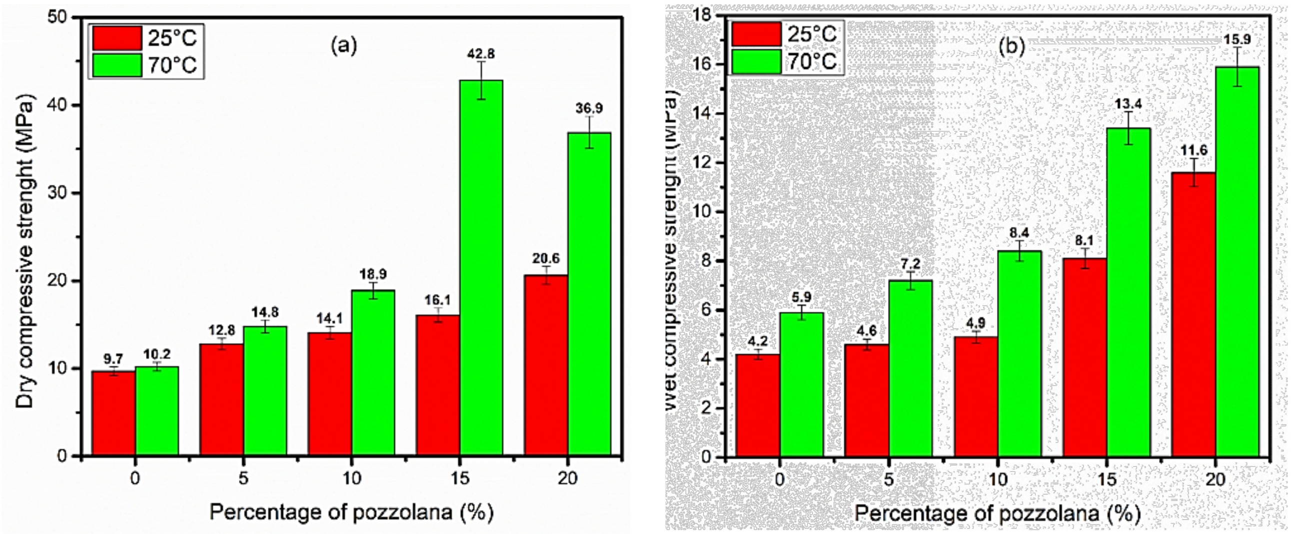

Fig. 4. *Compressive strength of stabilized Compressed Earth Blocks (CEBs) after curing at 25 and 70 °C under dry (a) and wet (b) conditions.*

Conclusion

Pioneered by Professor Joseph Davidovits, geopolymers have emerged as a promising avenue for sustainable construction materials. Defined by their inorganic nature and polymer-like structure, they offer a greener alternative to conventional materials. Initially focused on natural sources, recent research incorporates industrial byproducts like fly ash and ground granulated blast furnace slag, enhancing sustainability, accessibility, and economic viability.

Geopolymer composites, particularly alkali-activated materials, boast impressive qualities like fire and chemical resistance, high mechanical strength, and excellent durability. These properties have positioned them as viable substitutes for Ordinary Portland Cement since the early 1980s, aligning with global efforts to reduce carbon dioxide emissions.

Extensive research on fly ash and ground granulated blast furnace slag-based geopolymers showcases their versatility. Fly ash enhances moisture resistance and compressive strength, while the impact of ground granulated blast furnace slag depends on curing conditions and binder content. Their applications in soil stabilization and raw earth brick construction offer practical solutions, with environmental influences affecting their effectiveness.

Furthermore, utilizing pozzolana, a natural volcanic rock, as a geopolymer stabilizer expands the application scope. Phosphoric acid-activated pozzolana displays significant improvements in compressive strength, highlighting its potential in construction, particularly in challenging weathering conditions.

In essence, geopolymers have established themselves as a sustainable solution for construction, offering diverse applications and the potential to address environmental concerns associated with traditional building materials. The availability of the material used for this stabilization will determine which stabilization method to use, as both methods have a low greenhouse gas footprint.

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