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Durability Of Geopolymer Stabilization Of Expansive Soils - A Review

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Abstract: The stabilization of expansive soils, characterized by high plasticity, poses significant challenges in geotechnics due to their substantial volume changes and low strength. Recent advancements have introduced alkali-activated binders and geopolymers—derived from industrial by-products like fly ash, slag, metakaolin, rice husk ash, and zeolitic materials—as sustainable alternatives to traditional lime and ordinary Portland cement (OPC) for soil stabilization. This review consolidates both laboratory and field findings regarding the durability of geopolymer-stabilized expansive soils, examining their resistance to wetting–drying and wetting–soaking cycles, sulfate attacks, freeze–thaw cycles, leaching, long-term strength retention, and microstructural changes. We compare these mechanisms with conventional stabilizers, summarize the testing methods and durability metrics employed in existing literature, identify knowledge gaps (including standardization, long-term field monitoring, and the influence of local materials and activators), and propose research priorities for infrastructure applications. Key findings indicate that geopolymer stabilization generally enhances immediate strength, minimizes swell and shrinkage, and exhibits promising resistance to chemical and moisture cycles in contrast to OPC and lime. However, durability is highly dependent on precursor chemistry, Si/Al ratios, activator types and concentrations, curing conditions, and the presence of sulfates or chlorides. Evidence of multi-year field performance remains limited and necessitates coordinated long-term monitoring.

***Index Terms* -** Geopolymer, Alkali-activated binder, Expansive soil, Durability, Wetting-drying, Sulfate attack, Long-term performance.

I. INTRODUCTION

Expansive soils present a significant challenge in geotechnical engineering due to their tendency to swell and shrink with moisture variation. These soils, rich in clay minerals like montmorillonite, typically display high plasticity, low shear strength, and notable volume change characteristics, leading to potential damage to foundations, pavements, retaining structures, and embankments. The associated heaving and shrinkage can result in cracking, differential settlement, and failures in civil infrastructure, making their stabilization crucial. Traditional stabilization methods utilize lime and ordinary Portland cement (OPC) to lower the plasticity index, limit swelling potential, and enhance strength and stiffness. The hydration and pozzolanic reactions between these stabilizers and soil minerals create cementitious products like calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which bind soil particles and improve performance. However, these methods have limitations: lime and cement production are energy-intensive and contribute significantly to greenhouse gas emissions, with the cement industry responsible for approximately 7–8% of global CO_2 emissions. Additionally, the long-term durability of lime- or cement-treated expansive soils is not guaranteed, particularly in chemically aggressive environments where reactions such as ettringite formation can impair performance.

To overcome these issues, research has increasingly focused on low-carbon alternatives that utilize industrial by-products and waste materials. Geopolymers and alkali-activated binders (AABs) represent a promising category of materials. Geopolymers are inorganic aluminosilicate binders produced through the alkali activation of precursors like fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and rice husk ash. The geo polymerization process creates amorphous to semi-crystalline aluminosilicate networks, which enhance strength and chemical resistance.

Numerous studies have shown that geopolymer stabilization improves the strength and durability of expansive soils while promoting sustainability by utilizing industrial residues. Compared to traditional lime/OPC stabilization, geopolymers often demonstrate superior performance under varying moisture conditions and sulfate exposure. Nevertheless, challenges remain in translating laboratory results to reliable field applications, as the durability of geopolymer-stabilized soils relies on multiple factors, including mineralogy, precursor quality, activator concentration, and curing practices.

This paper critically reviews the durability of geopolymer-stabilized expansive soils, focusing on mechanical retention and degradation under various environmental cycles, resistance to sulfate and chemical attacks, leaching behavior, and microstructural changes that influence long-term performance. Additionally, it identifies research gaps and future directions for sustainable and durable stabilization of expansive soils using geopolymer technology.

II. GEOPOLYMER STABILIZATION: MATERIALS, REACTIONS, AND EXPECTED DURABILITY MECHANISMS

2.1 Materials and Activators

The effectiveness of geopolymer-stabilized expansive soils is significantly influenced by the selection of precursor materials and alkaline activators. The chemical composition and reactivity of the precursor, along with the concentration and type of activator, determine the characteristics of the geo polymeric gels formed.

2.1.1 Precursor Materials

Class F fly ash is widely used due to its abundance as a by-product of coal combustion. It is low in calcium and rich in amorphous aluminosilicate phases, which favor the formation of sodium aluminosilicate hydrate (N-A-S-H) gels upon activation. While fly ash-based geopolymers generally exhibit excellent long-term chemical resistance, they may require elevated curing conditions to achieve sufficient early strength.

Ground granulated blast-furnace slag (GGBS) is another common precursor that is rich in calcium. Its activation produces calcium–aluminosilicate hydrate gels (C-(N)-A-S-H), which resemble Portland cement hydrates but possess greater chemical stability. GGBS enhances early strength development but may vary in resistance to chemical attacks, especially under sulfate conditions.

Metakaolin, produced by calcining kaolinite clays, is highly reactive and forms dense gel matrices that enhance durability. However, its production requires thermal treatment, which adds energy costs compared to other industrial by-products.

Rice husk ash (RHA) and zeolitic tuffs are also being explored as sustainable precursors. RHA is rich in amorphous silica, while zeolites can influence ion transport and binding properties.

Various industrial wastes, including red mud and construction debris, have also been examined as alternative precursors, contributing to sustainability goals while necessitating careful characterization to ensure performance and environmental safety.

2.1.2 Activators

The choice of alkaline activator is crucial, with common options including alkali hydroxides and silicates. Alkali hydroxides initiate the dissolution of aluminosilicate species, while silicate activators provide soluble silica to enhance gel formation.

The activator modulus—a ratio of SiO_2 to Na_2O (or K_2O)—significantly affects gel chemistry and durability. Low-modulus activators can accelerate dissolution but may lead to weak matrices if polycondensation is insufficient. Conversely, high-modulus activators produce denser gels with enhanced stability but may slow reaction kinetics.

Research is also exploring alternative activators derived from industrial by-products, aligning with sustainable construction goals while requiring further standardization.

2.1.3 Influence of Precursor–Activator Chemistry on Durability

The combination of precursor and activator chemistry plays a pivotal role in determining the durability of the resulting geopolymeric gels. Low-calcium systems tend to form N-A-S-H gels, which exhibit superior sulfate resistance. In contrast, high-calcium systems can form C-(N)-A-S-H gels, which may behave differently in aggressive environments.

Furthermore, the Si/Al ratio influences gel structure, with lower ratios yielding more resistant gels. Optimizing this chemistry is crucial for achieving a balance between strength and long-term durability.

III. EXPERIMENTAL DURABILITY EVIDENCE: MOISTURE CYCLES, SULFATES, FREEZE–THAW, AND LEACHING

3.1 Wetting–Drying and Soaked Strength Retention

Laboratory studies indicate that geopolymer-stabilized expansive soils maintain a greater proportion of their unconfined compressive strength after wetting–drying or soaking compared to lime/OPC-stabilized soils. For instance, slag- and fly-ash-based geopolymers often show enhanced soaked CBR and UCS after moisture cycles.

3.2 Sulfate Environments

Sulfate attack is a major concern for expansive soils. Studies suggest that geopolymer binders—particularly low-Ca fly ash geopolymers—exhibit improved sulfate resistance relative to OPC due to their lack of portlandite, which is susceptible to ettringite formation. However, Ca-rich geopolymer systems may be vulnerable depending on their composition.

3.3 Freeze–Thaw and Physical Cycles

Research on freeze–thaw performance of geopolymer-stabilized soils is limited. Available evidence suggests that improved cohesion and reduced pore connectivity can mitigate frost damage, but freeze–thaw resistance is sensitive to curing conditions.

3.4 Leaching, Environmental Release, and Durability

Leaching behavior is critical for alkali-activated systems. Studies indicate low metal release when precursors are properly immobilized within the geopolymeric gel, but behavior varies with activator type and curing conditions. Durability assessments should incorporate both chemical stability and mechanical degradation metrics.

IV. MICROSTRUCTURE AND LONGEVITY: LINKING CHEMISTRY TO MACROSCOPIC DURABILITY

Microstructural analyses reveal that durable geopolymer-stabilized soils feature finer pore-size distributions and continuous gel matrices, reducing swell potential and increasing stiffness. The presence of unreacted particles and microcracks can predict future durability issues. Long-term monitoring is necessary to understand changes in durability over time.

V. COMPARATIVE PERFORMANCE WITH LIME/OPC

Comparative studies often demonstrate that geopolymer stabilization can match or exceed lime/OPC performance on metrics like UCS and resistance to moisture cycles and sulfates. However, traditional methods benefit from standardized procedures and extensive field experience, whereas geopolymer mixes require careful site-specific design and quality control.

VI. TEST METHODS AND METRICS USED IN DURABILITY STUDIES

Durability assessments of geopolymer-stabilized soils are vital for determining their performance under diverse environmental conditions. A range of testing methods has been developed to evaluate both the mechanical and chemical stability of these materials.

One primary method is the Unconfined Compressive Strength (UCS) test, which gauges the load-bearing capacity of soil samples without lateral confinement. This test is typically performed before and after conditioning, such as exposure to wetting-drying cycles or soaking. The UCS value, expressed in pressure units like kPa or psi, provides critical insights into the immediate strength of the stabilized soil and reflects its ability to support structural loads.

Another important test is the California Bearing Ratio (CBR) measurement, which assesses the strength of subgrade soil and base materials, especially for road construction. This test measures the resistance of soil to penetration by a standard piston under controlled conditions. Higher CBR values indicate better load-bearing capacity, making this metric crucial for determining the suitability of geopolymer-stabilized soils in infrastructure projects.

Wetting-drying cycle assessments further evaluate the durability of these soils by subjecting samples to repeated cycles of moisture saturation and drying. This test simulates real-world conditions and helps identify the soil's ability to cope with moisture fluctuations, which can lead to cracking and degradation. Metrics from this assessment include mass loss percentage, changes in UCS, and visual observations of any cracking.

Sulfate exposure testing is another key method used to evaluate the resistance of geopolymer-stabilized soils to sulfate attack, a frequent issue in sulfate-rich environments. This test helps identify potential long-term performance issues, as sulfate attack can lead to expansion and cracking that compromise durability. Metrics include changes in UCS, volumetric expansion measurements, and visual assessments of surface degradation.

Leaching tests and pH/conductivity monitoring focus on the environmental performance of geopolymer-stabilized soils by measuring the release of contaminants into leachate solutions. Understanding the leaching behavior is crucial for assessing the safety and environmental impact of these materials, particularly concerning heavy metal mobility. Metrics include pH levels, conductivity readings, and concentrations of contaminants in the leachate.

Lastly, microstructural analyses, which utilize techniques like Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Mercury Intrusion Porosimetry (MIP), provide valuable insights into the internal structure of geopolymer-stabilized soils. These analyses help identify gel networks, unreacted particles, and pore size distributions, correlating with the material's mechanical and chemical durability.

The variability in testing protocols and methodologies across different studies underlines the urgent need for standardized methods tailored for geopolymer-stabilized soils. Establishing consistent testing procedures will enable reliable comparisons, enhance the understanding of material performance, and promote broader acceptance of geopolymer technology in civil engineering applications.

VII. FACTORS CONTROLLING DURABILITY

The durability of geopolymer-stabilized expansive soils is influenced by a complex interplay of material chemistry, mix design, curing conditions, and environmental exposure.

7.1 Precursor Chemistry

The precursor's chemical makeup significantly affects the gels formed and their environmental resistance. A balanced Si/Al ratio is crucial for stable networks, while calcium content determines gel type and durability.

7.2 Activator Type and Concentration

Activator selection is critical; both under- and over-activation can compromise durability. Optimizing the activator modulus is essential for effective gel formation.

7.3 Curing Regime

Curing conditions impact the degree of polymerization and long-term durability. Balancing time, temperature, and moisture is vital for achieving optimal results.

7.4 Soil Mineralogy

The mineralogical composition of expansive soils influences stabilization performance. Different clay types exhibit varying swelling behaviors and stabilization requirements.

7.5 Aggressive Agents

Chemical environments affect durability; sulfates and chlorides can compromise stabilized matrices, necessitating careful mix design.

VIII. GAPS, CHALLENGES, AND RESEARCH NEEDS

Despite advancements, challenges remain in adopting geopolymer stabilization on a large scale. A lack of long-term field data, standardized testing protocols, and clear design guidelines hinders progress. Addressing these gaps through coordinated field studies and the development of low-impact activators is crucial for wider acceptance.

IX. CONCLUSIONS

Geopolymer stabilization presents significant potential for enhancing the durability of expansive soils compared to traditional lime and OPC solutions. Laboratory evidence supports improved performance metrics, yet durability remains dependent on specific mix designs and environmental conditions. Bridging existing gaps through coordinated research and standardized protocols is essential for broader application.

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