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EVALUATING THE PERFORMANCE OF GEOPOLYMER-BASED SOIL STABILIZATION COMPARED TO CEMENT AND LIME METHODS

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ABSTRACT

Soil stabilization is an important element of geotechnical engineering that improves the strength, durability, and load capacity of weak soil. Conventional stabilization methods like cement and lime treatment have gained extensive usage, but their effects on the environment, especially in terms of carbon emissions, necessitated research towards sustainable options. Geopolymer-based stabilization is a new avenue that has the potential because of its reduced carbon footprint, strength, and long-term durability. This research analyses the performance of geopolymer-based stabilization vis-a-vis normal cement and lime stabilization on primary factors including development of strength, durability under conditions of varying weathering, and sustainability. Theoretical investigation delineates the mechanism of reaction, engineering behaviour, and relative superiority of geopolymer-treated soil. Additionally, the research scrutinizes the environment and cost efficiency of large-scale application. Findings indicate that geopolymer-based stabilization provides a cost-effective and sustainable alternative to conventional methods, but optimization of material formulations and long-term performance are still challenging issues. Research directions for the future are suggested in order to promote the efficiency and usability of geopolymer-based stabilization in building and infrastructure works.

Keywords:Soil Stabilization, Geopolymer, Cement Stabilization, Lime Stabilization, Strength Performance.

1. INTRODUCTION

Stabilization of soil is an important aspect of geotechnical engineering as it enhances the strength, stability, and performance of soil to facilitate infrastructure construction. Soils in nature usually do not have enough bearing capacity and stability to withstand construction, resulting in possible problems like excessive settlement, erosion, and structure collapse. Stabilization methods are necessary to alter soil properties so that they can be more compatible with building foundations, road construction, embankments, and other geotechnical works [1].One of the main advantages of soil stabilization is that it can increase the strength and load-carrying capacity of weak soils. Most construction activities face problematic soils, like expansive clays or loose sands, which deform easily under heavy loads. Stabilization techniques, like mechanical compaction and chemical additives like cement, lime, or geopolymers, greatly increase the shear strength of soils as well as compressive strength. Through enhanced stability, these techniques avoid excessive settlement, making buildings safe and whole in the long run [2].Apart from strength enhancement, soil stabilization also increases durability by minimizing the influence of environmental factors like moisture variations and freeze-thaw actions. Unstabilized soils are very vulnerable to water entry, which causes swelling, shrinkage, and erosion. Chemical stabilization methods like lime and cement treatment modify the composition of the soil to increase its resistance against moisture-related problems [3]. Equivalently, geopolymer-based stabilization creates robuststructures that enhance water resistance and long-term soil strength, making it a very viable substitute for conventional processes. Another important component of soil stabilization is the role it plays in sustainability in geotechnical engineering. Traditional stabilization techniques, especially cement and lime stabilization, are very carbon intensive since the production processes of such materials require high amounts of energy. Conversely, geopolymer stabilization provides an eco-friendlier alternative by making use of industrial wastes such as fly ash and slag, thus minimizing dependence on cement but decreasing greenhouse gas emissions [4]. This transition towards sustainable stabilization methods harmonizes with contemporary engineering approaches towards environmentally friendly and resource-conserving construction. Aside from the environmental advantages, soil stabilization also maximizes cost savings in construction work. Through the enhancement of engineering characteristics of native soil, stabilization minimizes the use of costly excavation, transport, and replacement of unsuitable materials. This renders it a sensible solution for heavy-duty infrastructure schemes, such as road building, airport runways, and reinforcing foundations, where soil performance plays a crucial part in long-term safety and cost of maintenance. In general, soil stabilization is an integral element of geotechnical engineering to ensure that building projects are established on solid, long-lasting, and sustainable foundations [5]. As infrastructure needs accelerate, technological gains in stabilization processes, especially based on geopolymers, present exciting alternative options to the traditional techniques. Through the amalgamation of such new-age processes, geotechnical engineers have the potential to increase structural strength with decreased adverse effects on the environment, pointing towards more secure and sustainable infrastructure development.

Cement and lime stabilization are traditional methods of soil stabilization that have extensively been employed in geotechnical engineering for strengthening and hardening soils. While these stabilization methods have a lot of benefits, they have several drawbacks that affect their effectiveness, environmental acceptability, and durability. A major drawback with cement and lime stabilization is that they have high carbon footprints [6]. Cement and lime production are energy-hungry and have high carbon dioxide emissions, leading to environmental degradation and climate change. With increasing importance on sustainability in construction, there is growing demand for green alternatives. The other disadvantage of cement and lime stabilization is their sensitivity to soil type. These techniques function well in certain soils, including clayey soils, but could not function well in organic and saline soils. The interaction between lime and soil minerals is crucial for stabilization, and where chemical reactions that are necessary are inefficient, the process of stabilization is not efficient. This limits their applicability under varying geotechnical conditions. Also, cement and lime stabilization tend to result in extended curing times, which can protract construction activities [7]. Stabilized soil's strength development is dependent on pozzolanic reaction and hydration, which take sufficient moisture and time to provide the best possible outcomes. For aggressive infrastructure construction, this longer curing time becomes a drawback as opposed to other stabilization methods that ensure faster development of strength. Stabilized soil is also vulnerable to environmental influences. Cement-stabilized soils can develop shrinkage cracks that decrease durability, while lime stabilization can fail when wet, such that excessive soil moisture will disintegrate the soil-lime bonds. High sulphate in soil and freeze-thawing can further contribute to a decreased long-term stabilization effectiveness of such methods, ultimately resulting in structure failure and escalating maintenance needs [8].Economically, cement and lime stabilization is expensive in areas of poor access to these products. The cost of transportation and purchase of cement and lime contributes to the overall project cost, which makes it unaffordable in remote or developing regions. Further, the likelihood of leaching of lime and cement waste into groundwater raises environmental issues, compromising soil quality and water quality in the long term. Owing to such constraints, scientists and engineers are looking for alternative stabilization techniques, like geopolymer-based stabilization, that is as strong and durable as the traditional method but solves environmental and economic problems too. With the ongoing development of geotechnical engineering, a greater demand for sustainable and flexible stabilization technologies propels developments in soil treatment technology [9].

Geopolymer stabilization has emerged as a potent alternative to the conventional methods of soil stabilization as it possesses certain strengths, sturdiness, sustainability, and environmental friendliness. Perhaps its greatest advantage lies in its ecocompatibility. In contrast to cement and lime stabilization, which are responsible for significant production-related carbon dioxide emissions, geopolymer stabilization employs industrial waste products like fly ash, slag, and metakaolin, making it less reliant on traditional cementitious material. Apart from reducing environmental pollution, this also encourages sustainable construction by recycling waste products. Geopolymer-based stabilization has the additional benefit of high early strength and durability. Geopolymers have very fast polymerization reactions, hence developing strength much faster than that of cement and lime [10]. This renders them most ideal for use in projects involving rapid stabilization and initial load-bearing ability. The geopolymer-treated soils also display outstanding chemical attack, sulphate attack, and freeze-thaw resistance, thus maintaining stability in the long term even under adverse environmental conditions. This is especially useful in infrastructure projects within locations experiencing severe weather fluctuations. On the mechanical performance aspect, geopolymer stabilization improves the shear strength, compressive strength, and load-carrying capacity of the soil. The geopolymer matrix develops solid interlocks with soil particles, enhancing cohesion and limiting settlement problems. This translates into a more stable base, making geopolymer-treated soil well suited to applications like road construction, embankment, retaining walls, and foundation strengthening. Resistance to moisture is another benefit of geopolymer-based stabilization. Conventional lime stabilization may fail in high-moisture conditions, where high water content destabilizes soil-lime bonds [11]. Conversely, geopolymer-treated soils exhibit low permeability and high-water resistance, which renders them more consistent in waterlogged sites or areas subject to seasonal flooding. Economic viability is another impetus for the use of geopolymer stabilization. Although initial material prices may differ, the use of industrial waste materials for geopolymer manufacture can substantially lower overall costs in massive projects. In addition, the lower maintenance needs and enhanced longevity of geopolymer-stabilized soils translate to cost savings throughout the life of a structure. In general, geopolymer-based stabilization offers a cost-effective, sustainable, and long-lasting solution for enhancing soil characteristics in geotechnical applications [12]. Its strength-enhancing, environment-resistant, and carbon-emission-reducing capabilities make it an attractive substitute for conventional cement and lime stabilization. With ongoing research and technological innovations, geopolymer-based stabilization is likely to be a key player in the development of contemporary infrastructure.

2. SOIL STABILIZATION AND ITS PRINCIPLES

Soil stabilization is a basic geotechnical engineering process of improving the mechanical, chemical, and physical characteristics of soil in order to make it stronger, more durable, and more load-carrying. Natural soils tend to possess poor engineering qualities, including low shear strength, high compressibility, and susceptibility to changes in moisture, making them incapable of being used in construction [13]. Soil stabilization methods alter these characteristics to produce a more stable and durable base for infrastructure works, such as roads, highways, bridges, embankments, and foundations of buildings. The main aim of soil stabilization is to enhance the strength of the soil to resist applied loads, minimize settlement problems, avoid erosion, and provide durability to structures constructed on it. Soil stabilization efficiency is influenced by a number of important factors, such as soil type, moisture content, and curing duration. Soils of different types are characterized by their level of sensitivity to stabilization methods. For example, clayey soils, being high in plasticity and swelling potential, respond well to lime stabilization caused by the pozzolanic reactions enhancing soil cohesion and diminishing plasticity. Sandy soils, however, need to be stabilized using cement or polymer stabilizers to increase their strength of bonding. Moisture content is important in stabilization efficiency, as too much moisture can destroy the binding capabilities of stabilizers, while a lack of moisture can hinder chemical reactions from fully taking place. Water balance should be effectively attained to realize maximum development of strength in stabilized soils. Additional, curing time decides the stability of stabilized soils as chemical reactions such as hydration in cement stabilization or geo polymerization in geopolymer-based stabilization require time to reach their ultimate strength. Long curing gives the treated soil to attain its bearing capacity and, thus, makes it even better for use in construction. Engineering properties of stabilized soils greatly increase as compared to the original untreated soils and, hence, are more dependable in structural usage. One of the most significant enhancements is the shear strength increase, which increases the soil resistance to deformation and shear failure under loads. The compressive strength also improves with greater resistance to settlement and subsidence, an issue of concern in foundation work. The stabilized soils have lower permeability, which serves to prevent water penetration that causes erosion and structural weakening of the soil. This is particularly useful in road construction, where excessive water retention leads to pavement failure. In addition, stabilized soils exhibit greater resistance to environmental conditions like freeze-thaw cycles, sulphate attacks, and wet-dry weather fluctuations, guaranteeing long-term durability and lower maintenance costs. In addition to soil improvement, stabilization techniques also result in sustainability and cost savings in construction. Stabilization reduces the need for expensive excavation, transportation, and replacement of low-quality materials by enhancing the engineering parameters of available soil. This not only decreases construction cost but also minimizes the environmental impact by reducing the consumption of natural resources. The application of alternative stabilizers like geopolymers, which make use of industrial waste by-products like fly ash and slag, adds another layer of eco-friendliness to soil stabilization by encouraging waste recycling and the minimization of carbon emissions. In general, soil stabilization is an important process in geotechnical engineering that guarantees the stability and longevity of construction works. By overcoming the weaknesses of weak and unstable soils, stabilization methods offer a realistic and sustainable solution to enhancing soil performance. With increasing construction demands, improvements in stabilization technologies, especially geopolymer-based techniques, present promising alternatives to conventional cement and lime stabilization. Not only do these new methods increase soil strength and durability, but they also play a role in environmentally friendly and cost-effective infrastructure development.

3. CONCEPTUAL FRAMEWORK OF GEOPOLYMER-BASED SOIL STABILIZATION

3.1 Geopolymer Chemistry and Reaction Mechanisms

Geopolymer soil stabilization is based on geopolymer chemistry principles, where aluminosilicate-rich precursors react with alkaline activators to produce a cementitious binding matrix with high strength. Unlike conventional cementitious materials based on calcium silicate hydrate (C-S-H) gels for strengthening, geopolymers gain their strength from the formation of three-dimensional aluminosilicate networks and can be a proper alternative to traditional stabilization. The geopolymer-forming chemical reaction is a multifaceted process that includes dissolution, polymerization, and hardening of the gel, resulting in increased soil strength and resistance. The major raw materials employed for geopolymer stabilization are industrial by-products with high aluminosilicate content like fly ash, ground granulated blast furnace slag (GGBFS), and metakaolin. These substances are the foundation materials for geo polymerization, with the requisite silica (Si) and alumina (Al) content required for the reaction. Fly ash, one of the most widely used coal combustion precursors, contains reactive silica and alumina that are employed in the geo-polymerization process. Class F fly ash, with less calcium content, is generally used in soil stabilization because it is more durable and less susceptible to sulphate attacks. An industry by-product of steel, GGBFS is rich in calcium, which has the ability to accelerate early strength development in geopolymers. It is blended with fly ash to enhance geopolymer-stabilized soil performance. A thermally activated kaolinite clay, metakaolin is an extremely reactive aluminosilicate substance that plays a significant role in accelerated geo polymerization. It is highly efficient in enhancing cohesion and load-bearing properties of the treated soils. The choice of a suitable precursor is a function of the soil type, strength properties to be achieved, and environmental conditions at the stabilization location. An ideal balance of silica, alumina, and calcium content is important in achieving the best geopolymer performance.

Alkali Activation Process

Activation of the aluminosilicate precursors is done with alkaline activators like sodium hydroxide (NaOH) and potassium hydroxide (KOH), frequently supplemented with solutions of sodium silicate or potassium silicate. Alkali activation may be subdivided into the following steps:

1. *Dissolution: Reactive silicate (SiO_4) and aluminate (AlO_4) species are released into the solution when the alkaline activators dissolve the aluminosilicate linkages in the precursor material.*
2. *Hydrolysis and Polymerization: The aluminate and silicate species that are released react with one another to produce oligomeric structures, which gradually join to form longer polymeric chains.*

3. *Gel Formation: An amorphous or semi-crystalline gel structure starts to form as the polymerization process goes on. By encasing soil particles in a binding matrix, this geopolymer gel greatly improves the cohesiveness of the particles.*
4. *Hardening and Strength Development: Further polymerization and densification of the geopolymer network over time results in increased durability, decreased permeability, and improved mechanical strength.*

The effectiveness of the alkali activation process is influenced by a range of parameters, such as concentration of alkali, curing temperature, solid-to-water ratio, and reaction time. Increased alkali activator concentrations tend to enhance geo polymerization but can also contribute to excessive shrinkage or cracking. Hence, suitable optimization of these parameters is necessary to obtain durable soil stabilization.

Formation of Geopolymer Gels and Strength Development

The strength and stability of geopolymer-stabilized soils are largely attributed to the development of geopolymer gels, which constitute the major binding phase. In contrast to cementitious systems, which derive their strength from the development of C-S-H gels, geopolymers attain strength as a result of the development of sodium or potassium aluminosilicate hydrate (N-A-S-H or K-A-S-H) gels. These gels form a rigid, interconnected framework that improves the mechanical properties of the treated soils.

- *Early Strength Gain: The first phase of geo polymerization results in the development of a gel network, which quickly increases the strength of the soil within hours to days. The availability of calcium-rich precursors like slag can enhance early strength development.*
- *Long-Term Strength and Durability: Geopolymer-stabilized soils are resistant to sulphate assaults, freeze-thaw cycles, and moisture fluctuations because of the very durable matrix created over time by ongoing polymerization and structural densification.*
- *Reduced Shrinkage and Permeability: Compared to cement-stabilized soils, geopolymer-treated soils show less permeability and shrinkage, reducing the chance of water intrusion and cracking.*

The use of geopolymer technology in stabilization of soil is not only to enhance strength and durability but also to minimize environmental effects of classical cement and lime stabilization. The use of industrial by-products, coupled with lowered carbon emissions, makes geopolymer stabilization an environmentally friendly high-performance option for contemporary geotechnical applications.

3.2 Comparative Properties of Stabilized Soils

Geopolymer-based binder, cement, and lime stabilization of soil employs unique physical and chemical processes that affect the treated soil's performance properties. Although conventional stabilization by cement and lime has been employed for many decades, geopolymer-based stabilization has also proven to be a viable alternative as it exhibits superior durability, sustainability, and eco-friendliness. Stabilization of soil with various binders is characterized by specific chemical and physical processes that have a profound influence on the performance of the soil. Geopolymer stabilization depends on the development of N-A-S-H (sodium aluminosilicate hydrate) or K-A-S-H (potassium aluminosilicate hydrate) gels by a process referred to as geo polymerization. The reaction provides increased structural stability of the soil by forming a dense hard matrix. Conversely, cement stabilization generates C-S-H (calcium silicate hydrate) and C-

A-S-H (calcium aluminium silicate hydrate) gels during the process of hydration, resulting in quick early strength gain but causing the stabilized soil to be susceptible to shrinkage and cracking. Lime stabilization, however, entails the creation of pozzolanic products like calcium silicates and aluminates, which help in long-term strength gain but need longer curing times for complete reaction. Comparing early strength gain, cement stabilization has a notable edge as a result of its fast hydration process, enabling faster structural development. Geopolymer-based stabilization, though moderate in early strength development, is dependent on curing conditions and precursor composition. Soils stabilized with lime have the lowest rate of strength development, since the pozzolanic reaction is time-sensitive and necessitates proper curing for optimal outcomes. Yet when long-term strength is considered, geopolymer-based stabilization has the best outcomes due to ongoing densification of its aluminosilicate network, which makes it exhibit higher mechanical properties. Although cement stabilization also has high long-term strength, it is liable to suffer from shrinkage and cracking with the passage of time, thus lowering its overall durability. Lime-stabilized soil exhibits moderate long-term strength depending upon the type of soil and environmental factors. The most important factor influencing soil stabilization performance is moisture sensitivity. Geopolymer-stabilized soil is low in permeability and high in moisture resistance, thus being suitable for use where water stability is an essential requirement. Cement-stabilized soil has moderate permeability but is subject to moisture-induced degradation, especially in conditions with high exposure to water. Lime-stabilized soil is the most sensitive to moisture since it possesses high absorption of moisture, which can cause loss of strength under wet conditions. With regard to durability, geopolymer-based stabilization emerges superior once more with its high resistance against freeze-thaw and sulphate attacks and hence suitability for extreme environmental conditions. Cement stabilization offers intermediate resistance but is susceptible to sulphate-induced degradation, which can affect its long term. Lime-stabilized soil provides intermediate to high durability based upon the soil type and exposure conditions. Environmentally, geopolymer-based stabilization is a major plus. It is a low-carbon alternative because it only uses industrial wastes such as fly ash and slag, with a lower need for energy-driven manufacturing processes. Cement stabilization is, on the other hand, highly carbon-emitting because clinker manufacturing takes more energy compared to lime. Lime stabilization occupies a middle position where there is medium environmental implication resulting from the emissions of CO_2 during calcination of the lime. Also, with regard to shrinkage and cracking, geopolymer-based soil stabilization has minimal shrinkage due to its strong aluminosilicate matrix. Cement-stabilized soils have susceptibility to drying shrinkage and cracking that can cause long-term performance problems. Lime-stabilized soils have moderate shrinkage, but the degree varies with soil type and environmental factors. Considering cost and availability, geopolymer stabilization can be economical when industrial waste products are utilized as precursors. Alkali activator availability can be challenging in certain locations. Cement stabilization is easily available, but relatively expensive because the manufacturing process requires a lot of energy. Lime stabilization is widely available and less expensive than cement, making it a desirable alternative in cost-sensitive applications.

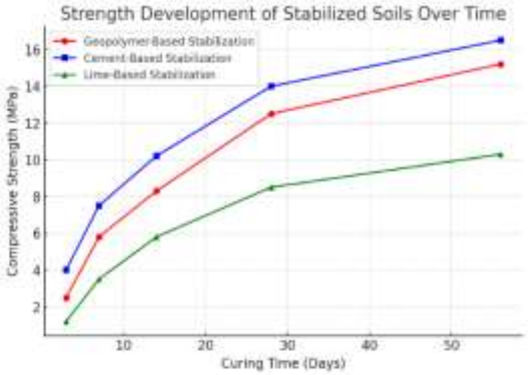

Fig: Strength Development Vs Time

The figure shows geopolymer, cement, and lime-stabilized soil strength development with various curing times. Cement-stabilized soil achieves early strength, whereas geopolymer-based stabilization has consistent increase over time and outperforms cement at advanced stages. Lime stabilization, as effective as others, has lower strength gain with time and, therefore, would not be very useful for areas where load-carrying capacity is needed soon. This comparison highlights the advantages of stabilization based on geopolymers in terms of sustainability and long-term durability. The effect of soil stabilization on soil structure and load-carrying capacity is an important parameter in assessing the effectiveness of different stabilization techniques. Stabilized soils experience structural modifications that improve their strength, decrease compressibility, and increase their load-carrying capacity. The most important measure of load-bearing capacity is the California Bearing Ratio (CBR), which quantifies the resistance of the soil to penetration under loaded conditions. Geopolymer stabilization considerably enhances soil load-bearing capacity through the development of a dense and hard aluminosilicate matrix. The reaction minimizes soil porosity and maximizes interparticle bonding, resulting in long-term strength gain. As indicated by the graph, geopolymer-stabilized soil has early moderate strength, but as curing extends, its CBR values increase progressively. At 28 to 56 days, CBR becomes greater than that of cement stabilization, rendering geopolymer-treated soil a superior long-term alternative. Cement stabilization creates rapid strength gain in the early stages by forming calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) gels. The graph indicates cement-stabilized soil performs better with increased CBR levels in the initial curing duration (3-14 days) than geopolymer-based stabilization. Eventually, though, the strength gain rate decreases, and durability factors such as shrinkage and cracking could impair it. All the same, cement stabilization is a common method applied in road engineering and foundation stabilization. Lime stabilization takes a slower strength gain curve, according to the graph. Pozzolanic reaction between clay minerals and lime needs long curing time to maximally improve soil properties. CBR values increase steadily for lime-stabilized soils, but their ultimate load-carrying capacity is less than cement and geopolymer stabilization. Nevertheless, lime stabilization is advantageous in the treatment of expansive soils through plasticity reduction and swelling potential.

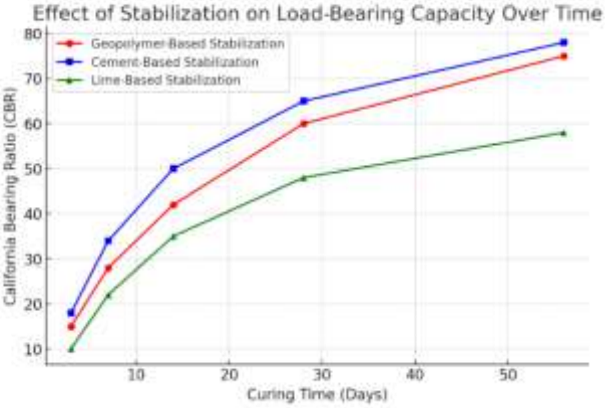

Fig: Stabilization Vs Time

3.3 Engineering Behaviour of Stabilized Soils

The engineering behaviour of stabilized soils is important in determining their suitability for different construction uses. Stabilization improves the mechanical properties of soil by modifying its structure, enhancing load-bearing capacity, lowering permeability, and reducing shrinkage or swelling. Various stabilization methodslike geopolymer-based, cement-based, and lime-basedhave varying effects on soil behaviour. It is important to know these effects to choose the most suitable method for particular engineering purposes. Stabilized soils have different stress-strain response and load distribution depending on the method of stabilization. Geopolymer-stabilized soil has a ductile nature at initial stages of curing, gradually becoming stiffer material due to continuous geo polymerization.

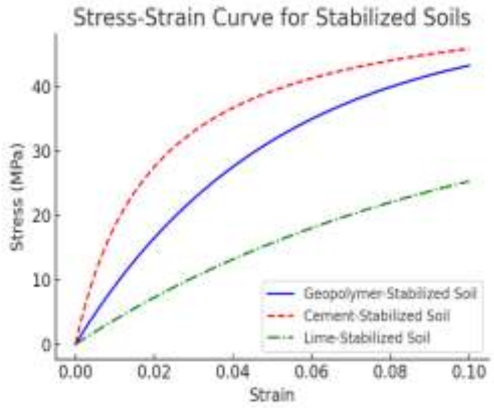

Fig: Stress-Strain Curve

This causes even load distribution, minimizing stress concentrations. Cement-stabilized soil, on the other hand, has high initial stiffness through quick hydration, but can end up with brittle failure under high load. Lime-stabilized soil develops continuously increasing stiffness, especially in soils with clay content, as pozzolanic reaction proceeds. Its long-term behaviour, however, is governed by soil mineralogy and curing conditions. Geopolymer-stabilized soils tend to be stronger but less brittle than cement-stabilized soils and thus better suited to long-term infrastructure applications.

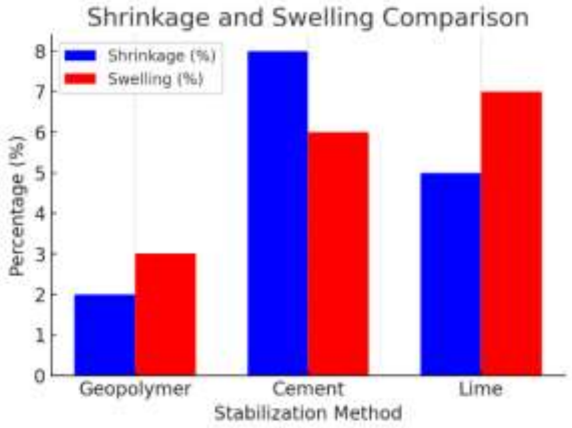

Fig: shrinkage and swelling characteristics

Shrinkage and swelling properties of the stabilized soils strongly affect their sustainability. Geopolymer-stabilized soil does not have a significant amount of shrinkage because the aluminosilicate matrix is formed with a strong, interlocking structure resistant to drying shrinkage cracks. Swelling capacity is also highly inhibited. Cement-stabilized soil is subject to drying shrinkage, which could cause surface cracks after a certain period. Although cement stabilization enhances swelling resistance over untreated soil, it still does not eradicate moisture-induced expansion. Lime-stabilized soil reduces swelling of expansive clays effectively by modifying their mineralogy but can also suffer from moderate shrinkage upon exposure to fluctuating moisture regimes. Field testing reveals that geopolymer stabilization is superior in terms of minimizing shrinkage-induced cracking and thus is very applicable to road building and embankment stabilization.

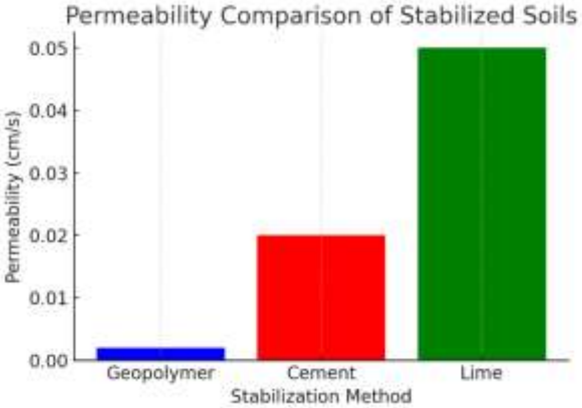

Fig: Permeability Comparison

The permeability and water-holding capacity of the stabilized soils define their durability to moisture variations and erosion. Permeability in geopolymer-stabilized soil is low, since the geopolymer matrix forms a dense network that does not permit water entry. This characteristic adds durability against weathering and environmental degradation. The permeability in cement-stabilized soil is moderate, yet hydration cracks over time can be a source of water entry and cause durability issues. Lime-stabilized soil is initially permeable, but as pozzolanic reactions enhance the structure of the soil, permeability reduces. Nevertheless, long-term water absorption can still influence performance. Geopolymer-based stabilization offers better resistance to water penetration, and hence it is a choice for applications where moisture durability is needed. The engineering implications of these characteristics are important. For foundation structures, geopolymer-stabilized soil offers durability and resistance to moisture over long terms and therefore can be considered an ideal solution for load-carrying structures. In construction roads, cement stabilization is regularly utilized due to high strength gain rates, yet stabilization based on geopolymers has more environmental sustainability and durability. For swelling soils, stabilization using lime minimizes swelling potential but geopolymer stabilization has more sustainability and durability.

4. COMPARATIVE ANALYSIS OF STABILIZATION TECHNIQUES

4.1 Strength Performance

The strength behaviour of soil stabilization techniques is of prime importance in their selection for construction and geotechnical applications. Among various stabilization techniques, geopolymer-based stabilization has been identified as a new trend replacing conventional cement and lime stabilization as it offers higher strength properties, sustainability, and environmentally friendly aspects. Strength performance is typically evaluated using Unconfined Compressive Strength (UCS) and shear strength testing, which aid in the determination of the load-carrying capacity and failure mechanisms of stabilized soils. UCS is widely used to determine the strength of stabilized soils via the test for the maximum axial compressive stress that the soil sample can withstand prior to failure. Increased UCS values suggest improved load-bearing capacity and durability over time. Likewise, shear strength testing evaluates the capacity of the soil to withstand shearing stress, which is important in slope stability, retaining walls, and foundation works. Geopolymer soils gain strength by forming N-A-S-H or K-A-S-H gels, while cement and lime gain strength from the development of C-S-H and pozzolanic reactions. Soils that are geopolymer-stabilized usually gain strength quickly under optimal curing conditions, whereas cement and lime take longer curing periods for complete hydration and pozzolanic reactions. Strength gains are affected by the presence of clay, silt, and sand differently by stabilization technique. Long-term strength is paramount for the stabilization soils' durability, especially for infrastructure developments. With time, geopolymer stabilization has a higher resistance to shrinkage, cracking, and geo-environmental degradation than conventional cement and lime stabilization. Geopolymer-treated soils have binding mechanisms that create a hard, chemically stable matrix that limits water-induced degradation and sulphate attack.

Table: Strength Performance Comparison of Stabilized Soils

Property	Geopolymer-Stabilized Soil	Cement-Stabilized Soil	Lime-Stabilized Soil

UCS (MPa) after 7 Days	2.5 - 5.5	3.0 - 6.0	1.5 - 4.0
UCS (MPa) after 28 Days	6.5 - 12.0	7.0 - 10.0	4.5 - 7.5
Shear Strength (kPa)	250 - 600	200 - 550	150 - 450
Long-Term Strength Stability	Excellent	Moderate	Moderate
Shrinkage and Cracking	Low	High	Moderate
Resistance to Moisture	High	Moderate	Low

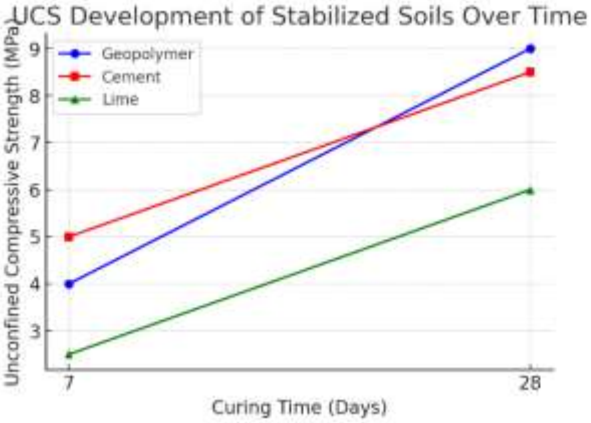

Fig: Unconfined Compressive Strength (UCS) Comparison

4.2 Durability Factors

Durability is the basic need for soil stabilization with long-term structural stability under multiple environmental and chemical conditions. Performance of stabilized soils is largely affected by their stability against moisture, freeze-thaw, and sulphate attack. Cement and lime stabilization have exhibited limitations in adverse environmental conditions, while geopolymer-based stabilization has proved higher resistance because of its special chemical composition and mechanism of binding. Freeze-thaw and moisture conditions have significant impacts on the long-term performance of soil stabilization. Exposed stabilized soils under high levels of moisture could undergo loss of strength, swelling, and cracking, while those experiencing freeze-thaw cycles can have micro-cracks, diminished load-carrying capacity, and disintegration. Geopolymer-stabilized soils are of low permeability and high water resistance based on their compact aluminosilicate matrix that does not allow moisture to intrude and sustain structural stability. Their high freeze-thaw resistance guarantees low strength loss even under harsh weather conditions. Cement-stabilized soils have moderate moisture and freeze-thaw resistance but are susceptible to micro-cracking with time, particularly under repeated freezing and thawing. Lime-stabilized soils are very sensitive to water changes. They absorb water, causing swelling, shrinkage, and considerable strength loss, especially in wet conditions. Chemical stability is necessary in soil stabilization, especially in sulphate-rich environments, acidic soils, or industrial pollution. Sulphates would react with stabilizers, resulting in expansion, cracking, and loss of strength. Geopolymer stabilization exhibits good resistance to sulphates because it is based on a low-calcium aluminosilicate reaction rather than hydration. It avoids expansive ettringite and Thomasite compounds' formation, which deteriorate cement and lime-stabilized soil. Cement-stabilized soils are very susceptible to sulphate attack because expansive calcium-sulphate compounds are formed, resulting in cracks and structural disintegration. Lime-stabilized soils exhibit fair resistance to sulphate attack but suffer deterioration from prolonged sulphate exposure.

Table: Durability Performance of Stabilized Soils

Durability Factor	Geopolymer-Stabilized Soil	Cement-Stabilized Soil	Lime-Stabilized Soil

Moisture Resistance	High	Moderate	Low
Freeze-Thaw Resistance	Excellent	Moderate	Poor
Sulphate Resistance	High	Low	Moderate
Acid Resistance	Strong	Weak	Moderate
Long-Term Stability	High	Moderate	Moderate

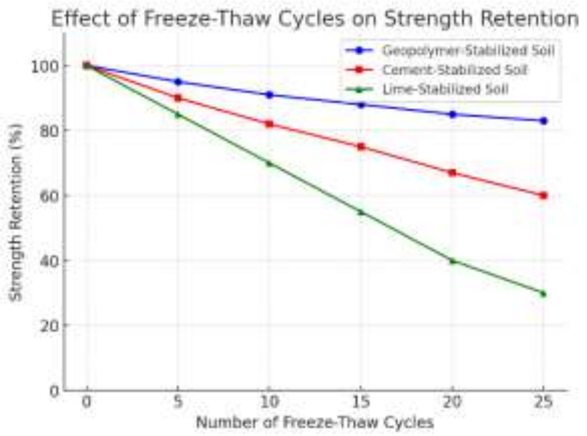

Fig : Effect of Freeze-Thaw Cycles on Strength Retention

The figure shows how various soil stabilization techniques preserve strength through several cycles of freeze-thaw. Geopolymer-stabilized soil has the highest strength preservation, exhibiting better durability than cement and lime stabilization.

4.3 Sustainability and Environmental Impact

Sustainability in construction and geotechnical engineering has emerged as an essential issue, particularly in soil stabilization practices. The need for environmentally friendly alternatives to traditional stabilizers such as cement and lime has led to interest in the use of geopolymer-based stabilization, with reduced CO_2 emissions, improved resource efficiency, and enhanced long-term sustainability. A comparative analysis of these methods of stabilization focuses on their environmental footprint, material efficiency, and life-cycle overall sustainability. One of the biggest environmental issues related to conventional soil stabilization techniques is the large carbon footprint of cement and lime manufacturing. Cement production is a power-hungry process, and it accounts for about 8% of global CO_2 emissions, mainly as a result of limestone calcination and fuel burning. Likewise, lime stabilization has a high contribution to CO_2 emissions, though less than that of cement. Geopolymer stabilization significantly lowers CO_2 emissions by using industrial waste products like fly ash, slag, and metakaolin, which bypass energy-intensive clinker production. Cement stabilization has high CO_2 emissions from its high-temperature production process, rendering it one of the least sustainable methods. Lime stabilization, while less carbon-emitting than cement, still includes CO_2 emissions from lime calcination and high energy use in production.

Table: CO_2 Emissions of Different Stabilization Methods

Stabilization Method	CO_2 Emissions (kg CO_2 per ton)	Environmental Impact
Geopolymer-Based	40–80	Low carbon footprint
Cement-Based	700–900	High carbon footprint
Lime-Based	500–600	Moderate carbon footprint

The economic viability of soil stabilization is a function of raw material availability, processing cost, and durability over time. Geopolymers are economical since they make use of industrial waste products like fly ash, slag, and metakaolin, thus minimizing virgin raw material dependency. This not only saves money but also encourages recycling of waste and efficient use of resources. Cement stabilization is available everywhere but costly because it is an energy-intensive process requiring high transportation costs. Lime stabilization is inexpensive and easily accessible but has variable effectiveness depending on the type of soil and needs supplementary pozzolanic materials to give better performance.

Table: Material Availability and Cost Comparison

Stabilization Method	Raw Material Source	Availability	Cost Effectiveness
Geopolymer-Based	Industrial by-products (fly ash, slag, metakaolin)	High	High
Cement-Based	Limestone-based cement	Moderate	Moderate
Lime-Based	Limestone (calcined)	High	Moderate

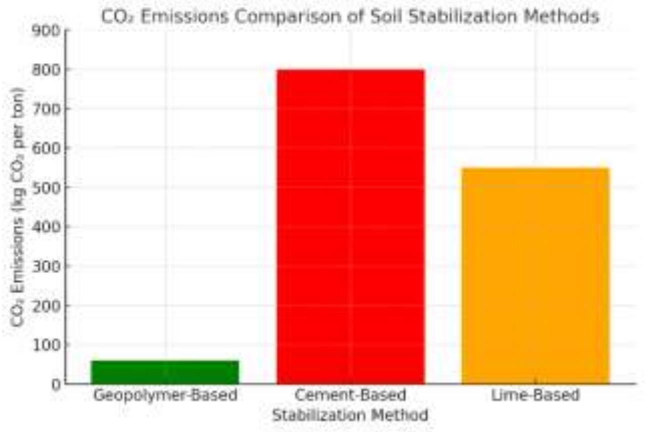

Fig: CO_2 Emissions Comparison of Stabilization Methods

The diagram shows CO_2 emissions per ton of CO_2 emissions by soil stabilization techniques. Geopolymer-based stabilization emits far less CO_2 than cement and lime and thus is the most environmentally friendly method.

5. CHALLENGES AND FUTURE DIRECTIONS

Although geopolymer-based stabilization has numerous benefits, there are a number of challenges that face its widespread use. One of the biggest limitations is the inconsistency in raw materials like fly ash and slag, which influences the homogeneity and effectiveness of geopolymer mixtures. In contrast to cement, which has widely accepted manufacturing standards, geopolymer stabilization involves the proper selection and treatment of aluminosilicate precursors to reach the desired strength and durability. Further, the process of alkali activation requires dealing with caustic solutions such as sodium hydroxide or potassium hydroxide, posing safety issues and demanding controlled mixing techniques. A further challenge is ensuring the long-term durability of geopolymer-stabilized soils under varied environmental conditions. Though research indicates great resistance to freeze-thaw conditions, sulphate attack, and moisture variation, more investigation needs to be carried out in its behaviour during extreme loading and seismic activity. Geopolymer stabilization compatibility with different soils is another research area that demands further exploration since the mineralogical composition dictates the reactivity of geopolymer binders. Field utilization and large-scale deployment also call for extensive validation of performance in order to come up with standard design guidelines for engineers and practitioners. Future improvement in geopolymer formulations has the potential to overcome these limitations by optimizing the binder composition and enhancing the efficacy of alkali activation. Investigation into novel activators, e.g., waste-stream-derived alkaline solutions, may lower costs and environmental footprint and preserve high performance. Nanotechnology and additive insertion, e.g., fibre reinforcement or bio-mineralization, may also optimize the mechanical behaviour and longevity of geopolymer-stabilized soils. More research is required to create predictive models for the behaviour of geopolymers in order to enable engineers to customize stabilization methods based on soil characteristics. Full-scale field tests and life cycle analyses are needed to prove the long-term advantages of geopolymer stabilization in practical applications. An interdisciplinary collaboration of researchers, industry players, and policymakers can support the development of standardized guidelines to encourage wider adoption of this environmentally friendly soil stabilization method. As innovation and research continue, geopolymer-based stabilization can potentially transform geotechnical engineering with a cost-saving, long-lasting, and green alternative to conventional methods.

6. CONCLUSION

This work introduced a comparative assessment of geopolymer-based stabilization of soil against traditional cement and lime stabilization methods. The study focused on the possible advantages of geopolymer-treated soils in terms of strength increase, durability, and environmental sustainability by examining their controlling principles, response mechanism, and engineering behaviour. Theoretical analysis indicated that geopolymer stabilization achieves equivalent, if not better, performance in mechanical properties while lowering considerably the carbon footprints and the use of conventional binders. Though geopolymer-based stabilization holds much promise, optimization of material formulations, long-term durability, and dealing with the intricacies of field applications still pose challenges. Future research will need to concentrate on optimizing geopolymer mixtures, varying alkali activators, and large-scale field tests to confirm laboratory evidence. In general, this research supports the sustainability and efficacy of geopolymer technology as a viable soil stabilization technique and opens the door for its wider use across geotechnical and infrastructure applications.

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