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INTEGRATIVE INSIGHTS INTO GEOPOLYMER-BASED SOIL STABILIZATION FOR SUSTAINABLE INFRASTRUCTURE

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ABSTRACT

Soil stabilization is an essential process in infrastructure development, conventionally based on cement and lime-based methods. Nevertheless, these conventional practices have environmental concerns in terms of high carbon footprints and consumption of resources. Geopolymers offer a likely substitute, with improved mechanical performance, sustainability, and durability. This study integrates key information on geopolymer-based stabilization of soils through assessing its physical, chemical, and mechanical effects on various soil types. A comparative analysis with conventional stabilizers emphasizes the advantages of geopolymers in higher strength, durability, and sustainability. The contributions of precursor composition, activators, and curing conditions are investigated to maximize the efficiency of soil stabilization. Environmental and economic viability for large-scale application is analysed using lifecycle cost analysis (LCCA) and carbon footprint minimization criteria. Findings demonstrate that geopolymers offer an effective, green alternative for sustainable infrastructure construction. The research concludes with suggestions for improved geopolymer uptake and avenues for future studies to tackle challenges of implementation.

Keywords: Geopolymers, Soil Stabilization, Infrastructure, Lifecycle Cost Analysis, Sustainability, Strength Enhancement, Environmental Impact

1. INTRODUCTION

A key step in the construction of infrastructure is soil stabilization, which guarantees the durability and structural soundness of buildings, bridges, roads, and other civil engineering projects[1]. The natural properties of soil vary widely; some are characterized by high compressibility, low bearing capacity, and erosion vulnerability. If not stabilized, these flaws can cause settlement problems, pavement failure, and decreased infrastructure lifespan, which may result in repairs and maintenance costs. Cement and lime treatment are among the traditional soil stabilization techniques that have been extensively employed to improve soil strength and durability [2]. These methods enhance the cohesion of the soil, decrease permeability, and counteract swelling or shrinkage due to water changes. Traditional stabilizers, though, have high carbon footprints, lead to environmental degradation, and deplete resources, making it essential to look for sustainable substitutes. The added emphasis on sustainable engineering and green building has led to the application of geopolymers as a green solution for soil stabilization. Geopolymers made from industrial waste such as fly ash and ground granulated blast furnace slag (GGBFS) have similar or superior performance compared to traditional stabilizers but with significantly reduced environmental footprint. Their properties to improve soil strength, durability against chemical attack, and long-term stability make them a potential substitute for large-scale engineering applications. As demands for infrastructure grow worldwide, there is a greater need for efficient, sustainable, and economical soil stabilization techniques. By incorporating cutting-edge materials such as geopolymers, engineers can create sustainable infrastructure with less environmental impact and high structural performance [3].

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Conventional soil stabilization methods, including cement and lime stabilization, have been extensively applied in infrastructure development to enhance soil strength, decrease permeability, and increase durability. Although these methods have been effective for decades, they are associated with considerable limitations that influence their long-term sustainability, economic viability, and environmental footprint [4]. One of the main disadvantages of traditional stabilization methods is their carbon intensity. Cement and lime production are energy-demanding processes that emit high levels of CO_2 into the environment. Cement production alone accounts for almost 8% of all CO_2 emissions, and thus it is a significant environmental issue. With increasing emphasis on sustainability in contemporary construction, there is an increasing demand for lower emission stabilization methods. Another significant drawback of conventional stabilization approaches is their reliance on natural resources [5]. The mass production of limestone for cement and lime extraction exhausts natural resources, resulting in ecological imbalance and more environmental degradation. The quality of raw materials also differs geographically, resulting in logistical issues and cost increases in regions where cementitious material transportation is necessary. This reliance on non-renewable resources makes conventional stabilization methods less sustainable in the long term. Durability is also a key problem in traditional stabilization techniques. Cement- and lime-treated soils can be affected by sulphate attack, leading to cracking, swelling, and final failure of the stabilized layer. This can be a particularly sensitive issue for soils with high sulphate levels or areas having high groundwater sulphate levels. Additionally, soils that are stabilized using cement can undergo shrinkage and cracking owing to moisture content fluctuations, minimizing their long-term suitability for applications in infrastructure development. These durability issues require extensive repairs and maintenance, raising the total lifecycle expenditures of building projects. Besides environmental and durability issues, conventional soil stabilization methods involve long curing periods before the stabilized soil attains its required strength [6]. Cement-stabilized soils, for example, usually require several days to weeks to gain ultimate strength, which leads to delays in time-constrained infrastructure developments. Compared with alternative stabilization approaches, such as geopolymers, there is more rapid gain in strength so that projects are completed more rapidly. Another weakness is the differing performance between soils of varying types. Although cement and lime work adequately with clayey and silty soils, they are not able to provide a similar level of stabilization in sandy or organic soils. Because of this restriction, extensive laboratory research and site-specific mix design are required, which raises the expense and complexity of stabilization programs. In addition, long-term behaviour of cement-stabilized soils to dynamic loads, such as on road pavements and embankments, continues to be of concern because it suffers from fatigue and wear through the passage of time. Lastly, the cost-effectiveness of conventional stabilization methods has to be taken into account. Though cement and lime stabilization have long been employed through their availability and efficacy, growing raw material cost, combined with transport costs as well as ecological compliance, make such techniques more economically unappealing in projects involving large structures. As the regulatory pressure to cut down carbon emissions and adopt sustainable building methods increases, the cost of utilizing conventional stabilizers is bound to rise, forcing the sector to turn to alternative options such as geopolymers [7].

Geopolymers are a green replacement for conventional soil stabilization techniques that provide substantial environmental, economic, and performance benefits over cement- and lime-based stabilizers. Inorganic aluminosilicate geopolymers are made from industrial by-products like fly ash, ground granulated blast furnace slag (GGBFS), and metakaolin activated by alkaline solutions.

Compared to traditional stabilizers, geopolymers have lower energy requirements in production and release very little CO_2, making them a green option for contemporary infrastructure construction [8].One of the major advantages of geopolymers for soil stabilization is their lower carbon footprint. Conventional stabilizers, especially Portland cement and lime, are responsible for large amounts of greenhouse gas emissions as they are produced using high-temperature processes. Geopolymers, on the other hand, employ industrial waste products that would otherwise end up causing landfill build-up, thus supporting circular economy practices. Research has established that geopolymer-based stabilization can lower CO_2 emissions by as much as 80% from cement-based methods in compliance with international sustainability standards and green building policies. Geopolymers also possess better mechanical characteristics, which makes them extremely useful in soil strength and durability improvement [9]. The polymerization reaction within geopolymers creates a dense, coherent matrix that encapsulates soil particles, greatly enhancing load capacity and resistance to environmental forces. This enhanced development of strength enables stabilization of a broad spectrum of soils, such as clayey, silty, and sandy soils, rendering geopolymers a general-purpose solution for diverse infrastructure applications like road pavements, embankments, and foundation stabilization. The other main benefit of geopolymers is their very good resistance to chemical attack. Conventional cement-based stabilizers are vulnerable to sulphate attack, resulting in cracking and degradation over time, particularly in sulphate-rich conditions. Geopolymers, however, possess superior chemical durability, resisting extreme environmental conditions, such as high levels of sulphates and acidic conditions [10]. This renders them especially ideal for use in aggressive ground conditions, where long-term stability is paramount. Aside from environmental and durability advantages, geopolymers show increased strength gain over cement stabilization. Cement-stabilized soils take often months of curing to develop peak strength, pushing forward construction timelines. Geopolymer-treated soils develop high early strength within a shorter period of curing, allowing for quicker project completion and minimizing project costs overall. In addition, geopolymers have less shrinkage and fewer cracking propensities, which increase the durability and performance of the stabilized soil layers. Cost-effectiveness of geopolymer-based stabilization also further enhances its attractiveness for use in mass-scale infrastructure projects. Although initial costs of alkaline activators and processing are marginally more compared to traditional stabilizers, long-term advantages such as lower maintenance costs, increased durability, and fewer environmental compliance costs lead to net economic savings. Furthermore, the use of industrial byproducts as raw materials offers a cost-efficient and environmentally friendly substitute for virgin resources, rendering geopolymer technology economically viable for mass application [11].

2. SYNTHESIS OF KEY FINDINGS ON SOIL STABILIZATION TECHNIQUES USING GEOPOLYMERS

1. Mechanical Effects: Strength Enhancement, Load-Bearing Capacity, and Compaction

Mechanical soil stabilization with geopolymers is mainly for strengthening, load capacity, and improving compaction. Polymerization of geopolymer precursors such as fly ash, GGBFS, and metakaolin leads to the formation of a compact aluminosilicate matrix that bonds soil particles together. The UCS and CBR increase, making geopolymer-stabilized soils proper for foundation, pavement subgrade, and embankment stabilization applications. Studies have shown that geopolymer-stabilized soils can achieve UCS values above 5 MPa depending on curing conditions and precursor type. This increase in mechanical strength is especially useful for

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infrastructure applications with the need for long-lasting, high-strength subsoils. Geopolymer-stabilized soils are also more stiff and less deforming under load, ensuring stable structures in the long term. Soil compaction behaviour is also highly affected by geopolymers. As compared to cement-based stabilizers that may lead to excessive water loss and cracking, geopolymer-treated soils achieve optimal moisture content, leading to enhanced workability and reduced shrinkage on drying. The reduced water demand of geopolymer reactions minimizes the risk of volumetric instability, preventing differential settlement in roadways and buildings' foundations.

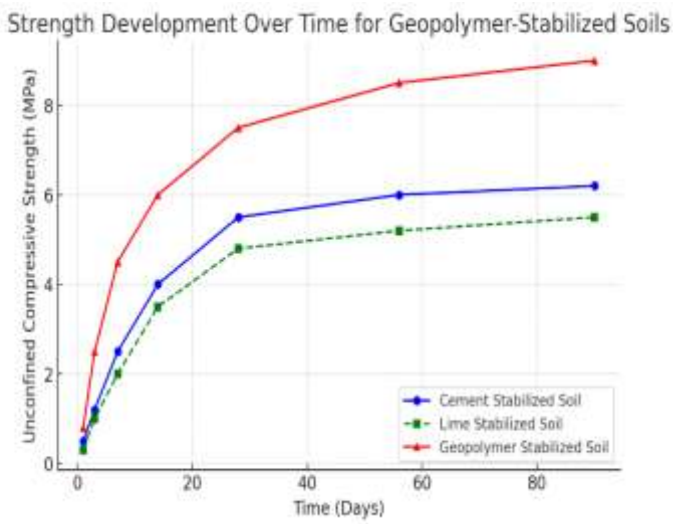

Fig : Strength Development Over Time for Geopolymer-Stabilized Soils

2. Chemical Effects: Reaction Mechanisms, Mineral Transformations, and Soil Stabilization Chemistry

Alkaline activation of chemical stabilization of soil by geopolymers is regulated by the dissolution and polymerization of alumina (Al) and silica (Si) from precursor materials. The formation of N-A-S-H (sodium-alumino-silicate-hydrate) and C-A-S-H (calcium-alumino-silicate-hydrate) gels is credited with soil binding and long-term stability enhancement. Activation begins with the dissolution of aluminosilicate precursors within an alkaline solution of either NaOH or KOH. This creates reactive species that then polymerize to form a three-dimensional network of geopolymer. In the long term, geopolymer-treated soils undergo the generation of cementitious compounds, enhanced strength and durability. In contrast to cement that is dependent upon calcium silicate hydrate (C-S-H) gel formation, geopolymers are based on Si-Al linkages that offer better chemical resistance and less shrinkage. The incorporation of alkaline activators accelerates the pozzolanic reaction to improve sulphate resistance, pH stability, and minimize leachability of heavy metals in contaminated soil. Geopolymers are thus most apt for stabilization under chemically aggressive conditions.

3. Physical Effects: Shrinkage Reduction, Permeability Changes, and Durability Improvements

Shrinkage behaviour, permeability, and long-term strength of soil are enhanced considerably with the geopolymer stabilization. Geopolymers have low shrinkage because their water-cement ratio is lower compared to regular stabilizers. It means fewer shrinkage cracks, minimizing the possibility of structural failure in pavement structures and foundations. As compared to cement-stabilized soils that tend to have excessive shrinkage because of changes in moisture, geopolymer-treated soils are dimensionally stable across different environmental conditions. Geopolymer-stabilized soil has lower permeability than that of untreated or cement-stabilized soil. The geopolymer matrix cements the micropores in the soil, minimizing the likelihood of water penetration, erosion, and frost heave. Such a characteristic is especially beneficial in road development, protection against flooding, and underground works. Geopolymers show higher resistance to chemical attack, freeze-thawing, and sulphate exposure than conventional cementitious materials. The durability is ensured for long-term performance under severe environmental conditions with less frequent maintenance and reconstruction.

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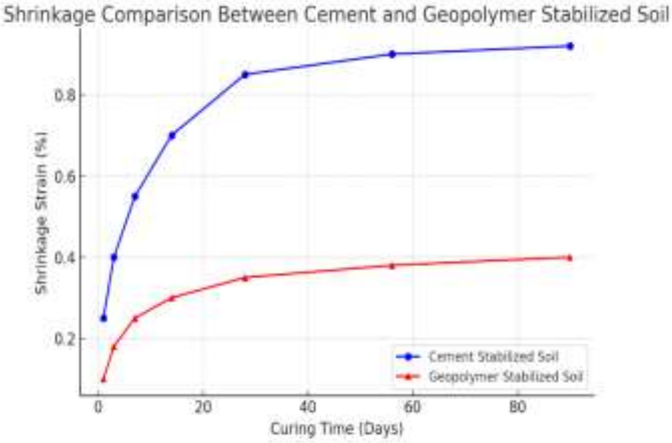

Fig : Shrinkage Comparison Between Cement and Geopolymer Stabilized Soil

Geopolymer soil stabilization is a very efficient and sustainable substitute for traditional stabilizers. The mechanical enhancements, such as enhanced strength and improved compaction, render geopolymer-treated soils more dependable for infrastructure applications. The chemical stability of geopolymers offers better sulphate resistance attack and encapsulation of heavy metal, and the latter are adequate for unfavourable geotechnical conditions. Besides, physical benefits, such as reduced shrinkage and less permeability, increase long-term durability and environmental sustainability of stabilised soils by geopolymers.

3. SYNTHESIS OF KEY FINDINGS ON PERFORMANCE EVALUATION OF GEOPOLYMER-BASED SOIL STABILIZATION

Geopolymer-based stabilization of soils has become a potential and green alternative to traditional techniques based on cement and lime. The demand for sustainable solutions for infrastructure has prompted researchers and engineers to seek geopolymers because of their excellent mechanical behaviour, long durability, and considerably reduced carbon footprint. In contrast to conventional stabilizers, which are based on pozzolanic and hydration reactions to improve soil characteristics, geopolymers involve a distinctive polymerization process. Three-dimensional aluminosilicate gels are created when aluminosilicate-rich precursors, such as fly ash, ground granulated blast furnace slag (GGBFS), and metakaolin, combine with an alkaline activator. These three-dimensional aluminosilicate gels behave as a high-strength binder, enhancing much more the soil's structural property and minimizing its environmental footprint. Conventional cement and lime stabilization methods have been extensively practiced in soil engineering for the purpose of upgrading load-carrying capacity, limiting shrink-swell behaviour, and sustaining durability. The foundation of cement stabilization is hydration processes, which produce the calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) phases that harden the soil. Lime stabilization, by contrast, is very effective in treating highly plastic and expansive soils since it generates pozzolanic reactions that convert clay minerals to more stable products. However, such conventional processes also possess some noteworthy drawbacks, including high energy utilization, high production-related carbon dioxide (CO_2) emissions, and susceptibility to long-term degradation due to sulphate attack and shrinkage cracking. Geopolymers, however, exhibit excellent mechanical behaviour, often performing better than their conventional stabilizers in strength and durability. Cement-stabilized soils generally develop strength rapidly, but geopolymer-stabilized soils develop the same or greater long-term strength, depending upon the type of precursor, content of alkaline activator, and curing regimes. Research indicates that geopolymer-stabilized soils have the ability to achieve higher compressive strength due to the denser microstructure developed by aluminosilicate gels that are polymerized. Further, geopolymer-treated soil with its low permeability prevents more water to penetrate the ground and makes erosion and long-term stability easier. One other huge benefit of using geopolymers is the speed at which it sets and their improved sustainability. Whereas lime stabilization would need months for curing so as to get optimal strength, stabilization through geopolymer technology could obtain massive strength within less time. This faster performance is especially valuable for major infrastructure projects where the construction schedule is important. In addition, incorporation of industrial waste materials like fly ash and slag in geopolymer mixtures aids in waste valorisation, reducing the environmental impact of conventional soil stabilization methods. In addition to their mechanical benefits, geopolymers provide a significant decrease in CO_2 emissions over cement and lime. The manufacture of Portland cement, one of the main constituents of conventional stabilization, is a primary cause of carbon emissions across the globe, with estimates indicating that the production of cement contributes towards around 8% of the world's CO_2 emissions. On the other hand, geopolymer synthesis involves waste products from industries, processed at lower temperatures and releasing much less CO_2, hence proving to be a more eco-friendly option for infrastructure development. Moreover, geopolymers are found to resist chemical degradation much better than ordinary materials and, therefore, have great potential for use in harsh environmental conditions. Traditional cement-stabilized soils are susceptible to sulphate attack, potentially resulting in expansive ettringite and consequent cracking. Geopolymers, however, show high resistance to sulphate exposure, freeze-thaw action, and acid attack, which can provide assured long-term performance in harsh environments.

Strength, Durability, and Long-Term Stability Considerations

One of the most important considerations when assessing soil stabilization techniques is whether they can enhance the load-bearing capacity and strength of treated soils. Research suggests that geopolymer-stabilized soils demonstrate high resistance to shrinkage, sulphate attack, and freeze-thawing, and so are extremely appropriate for use in infrastructure. The geopolymer-based stabilization process also greatly lowers permeability, thus increasing resistance to water flow and erosion into and through soils. Long-term stability evaluations prove that geopolymers also develop strength over a period, while cement-treated soils can have cracks due to drying shrinkage. The durability of geopolymer-treated soils is improved through their compact microstructure and superior binding efficiency, allowing for a long service life of infrastructure structures. Moreover, geopolymers' capacity to support various soil types, including expansive and loose sandy soils, reveals that they are apt for large-scale application in road construction, embankments, and foundation strengthening.

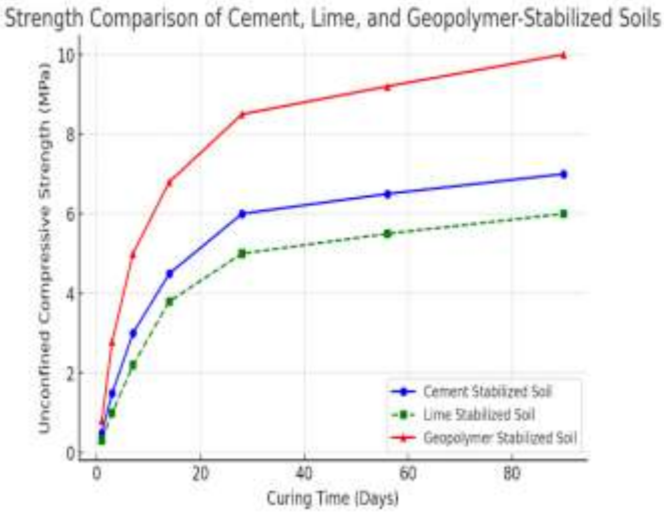

Fig : Strength Comparison of Cement, Lime, and Geopolymer-Stabilized Soils Over Time

4. SYNTHESIS OF KEY FINDINGS ON GEOPOLYMER COMPOSITION AND CURING CONDITIONS

Selection and blend of aluminosilicate precursors are key to the regulation of geopolymer-based soil stabilization performance. Several precursors like fly ash, ground granulated blast furnace slag (GGBFS), and metakaolin possess particular chemical and physical composition that influences geo polymerization. With a comprehension of each type of precursor's unique contributions, engineers can customize geopolymer formulations for optimal stabilization efficiency across diverse soil environments. Fly ash is the most widely used precursor in geopolymer recipes because it is available and has pozzolanic activity. Class F fly ash, consisting primarily of silica (SiO_2) and alumina (Al_2O_3), requires a strong alkaline activator, for instance, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), to initiate geo polymerization. This results in the formation of sodium-alumino-silicate-hydrate (N-A-S-H) gels, imparting long-term durability and strength. However, due to the lack of high calcium content, Class F fly ash possesses reduced reaction kinetics and hence early development of strength is delayed. Conversely, Class C fly ash possesses a higher percentage of calcium (CaO) thus there exists a combination of pozzolanic as well as geo polymerization reactions. The presence of calcium-alumino-silicate-hydrate (C-A-S-H) gels enhances early strength development, and Class C fly ash is an excellent precursor for use in applications requiring rapid development of strength. Its performance, however, relies heavily on the particular composition and curing conditions, and its incorrect mixing may cause unstable stabilization results. GGBFS is a very reactive precursor because of its high calcium content, which supports quick geo polymerization when it is mixed with alkaline activators. The main reaction products are C-A-S-H gels that increase soil bonding, decrease permeability, and increase resistance to environmental degradation. GGBFS is superior to fly ash in terms of early strength development, and hence, it is the best precursor for applications involving quick stabilization. GGBFS also enhances sulphate resistance and controls shrinkage-related problems, resulting in long-term durability in hostile soil conditions. Its high reactivity enables the reduction of activator dosage, thus making it an economical option for large-scale infrastructure development. Excess usage of GGBFS may, however, cause brittle geopolymer concrete structures, which requires careful optimization of precursor blend ratios. Metakaolin is a highly reactive ultrafine aluminosilicate product resulting from thermal activation of kaolinite clay. Metakaolin contains a high SiO_2-to-Al_2O_3 ratio, which supports low-porosity dense geopolymer structures. Initiation of metakaolin-based geopolymers with an alkaline solution produces high mechanical strength, chemical resistance, and long-term stability. Due to its high reactivity, metakaolin performs best in high-performance stabilization systems where durability is a significant requirement. It increases geopolymer density, minimizes shrinkage, and increases sulphate and acid attack resistance. Metakaolin is comparatively costly compared to fly ash and GGBFS, which restricts its use in large-scale infrastructure projects.

Role of Activators, Curing Temperatures, and Moisture Conditions

The performance of geopolymer-based soil stabilization is also strongly influenced by alkaline activators, curing temperature, and humidity. These are directly responsible for the dissolution of aluminosilicate precursors, rate of gel formation, and end-mechanical strength of stabilized soil. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are typical examples of alkaline activators needed to break down aluminosilicate bonds so that the polymerization of geopolymer gels is possible. The concentration of activators and the activator ratio determine the rate of reaction and final strength of stabilized soil. Precursor dissolution accelerates with increasing NaOH concentration, resulting in fast geo polymerization. Increasing activator dosing, though, can inject excessive porosity, undermining mechanical stability. Optimum NaOH concentration is normally between 8M and 12M, striking a balance between reactivity and strength development. Further, the addition of sodium silicate promotes gel network development, exhibiting greater durability and less shrinkage. Temperature of curing plays a significant role in controlling the rate of geo polymerization. Increased temperatures increase the dissolution of the aluminosilicates and improve gel development, resulting in better compressive strength. Experimental findings show that curing at 60–80°C for 24–48 hours considerably accelerate early strength development.

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Nonetheless, in real-world applications, ambient curing conditions are usually favoured because of economic and logistical limitations. Ambient curing, although it might take longer periods (up to 28 days) to attain maximum strength, is still a feasible method for large-scale applications. The choice of precursors and activators can also reduce the necessity for high curing temperatures, allowing for effective stabilization under field conditions. Proper moisture conditions during geopolymer curing is critical to avert early drying and incomplete polymerization. Maintaining proper moisture conditions guarantees symmetrical gel growth and improves long-term stability in stabilized soils. Low moisture levels can result in low reactivity, leading to lower strength, higher porosity, and eventually failure. Leaching of the alkaline activators due to high moisture might result in efficiency loss in geo polymerization. Field observations indicate that controlled curing with moisture, along with surface sealing methods, greatly enhances the mechanical behaviour of geopolymer-stabilized soils. To ensure maximum efficiency in geopolymer-based stabilization of soil, optimization methods have been developed. These methods centre on improving precursor blending, activator selection, and curing procedures to develop enhanced mechanical and durability properties.

1. Blended Precursors

Mixing various precursors enables to optimize the strength development and toughness. Mixing of fly ash with GGBFS, for instance, balances both early and durability gains. Mix of 70% fly ash and 30% GGBFS has proven to give optimum performance, registering both enhanced early strength and durability.

2. Hybrid Activation

Application of a mixture of sodium hydroxide and sodium silicate facilitates the development of a strong geopolymer gel network. Hybrid activation increases the bonding of the soil, decreases shrinkage, and provides uniform strength development. With precise adjustment of the activator ratio, the stabilization process can be considerably enhanced in efficiency.

3. Controlled Curing Conditions

Using temperature-controlled curing for the first 48 hours, then ambient curing, is an enhancement to improve geopolymer strength and reduce cracking. This method is especially useful in large engineering projects where curing methods with minimal energy usage are needed.

4. Additive Incorporation

The addition of nanoparticles, fibres, or pozzolanic materials like silica fume further improves the mechanical characteristics of geopolymer-stabilized soils. These additives enhance resistance to weathering, lower permeability, and improve long-term stability. Studies have indicated that the addition of nano silica can improve compressive strength by as much as 20%, and thus it is a promising method for high-performance stabilization applications.

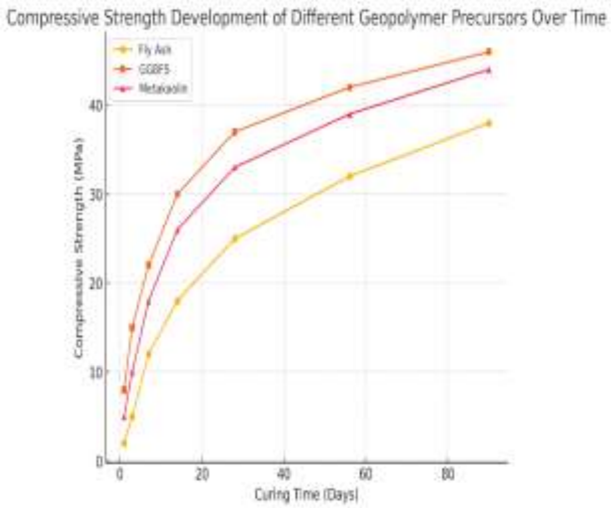

Fig : Compressive Strength Development of Different Geopolymer Precursors Over Time

5. SYNTHESIS OF KEY FINDINGS ON ENVIRONMENTAL AND ECONOMIC FEASIBILITY

Lifecycle Cost Analysis or LCCA is a useful device for economic comparability analysis for geopolymer soil stabilization as compared to standard methods such as cement and lime stabilization. It considers the material costs initially, processing and delivery costs, building, upkeep, and longevity in the long run. While the upfront cost of geopolymer stabilizers is higher due to the need for alkaline activators (e.g., sodium hydroxide and sodium silicate), their long-term benefits over traditional methods are due to their increased durability, lower maintenance requirements, and extended lifespan. Research shows that geopolymer-stabilized soils have lower rates of deterioration, reducing the frequency of expensive repairs in infrastructure works. In addition, the use of industrial byproducts like fly ash and GGBFS lowers raw material costs considerably. In highway, airport, and embankment applications on a large scale, the cost benefit of geopolymers is accentuated by economies of scale and lower lifecycle costs. Perhaps the most important benefit of geopolymer soil stabilization is its capacity to lower carbon emissions. Conventional cement production is accountable for almost 8% of all CO_2 emissions, while geopolymer manufacturing has the potential to reduce emissions by as much as 80% by using industrial waste products rather than energy-hungry clinker production. Moreover, polymerization in geopolymers releases significantly less CO_2 than cement hydration reactions. Geopolymer-stabilized soil also has lower energy demands for manufacture and curing, particularly at ambient temperatures, lowering its environmental impact even further. These aspects render the geopolymers a greener option for infrastructural projects committed to reducing their carbon footprint.

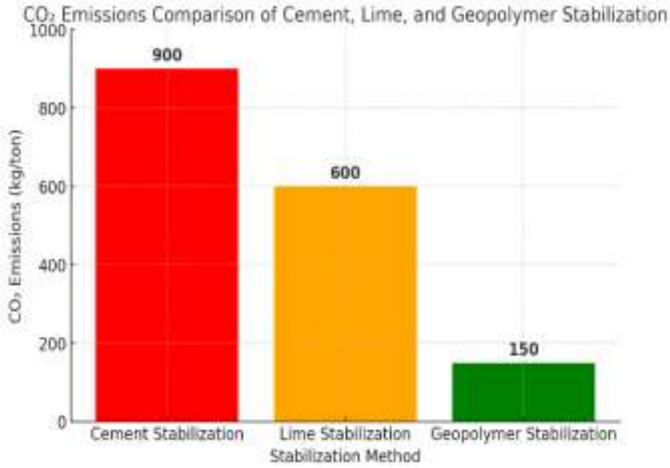

Fig : CO_2 Emissions Comparison of Cement, Lime, and Geopolymer Stabilization

Geopolymers offer a new way of making use of industrial waste products like fly ash, GGBFS, and metakaolin, mitigating environmental impacts while enhancing the efficiency of soil stabilization. The circular economy principle guarantees that industrial by-products, which could otherwise lead to waste generation, are efficiently utilized. In addition, geopolymer-stabilized soil exhibited increased resistance to sulphate attack, shrinkage, and erosion due to water, resulting in longer service life and lower maintenance. The long-term economic effect is considerable, since infrastructure works involving geopolymers have fewer structural failures, less rehabilitation cost, and better durability against harsh weather conditions.

6. CONCLUSION

This research brings to light the promise of geopolymer-based soil stabilization as a sustainable method of stabilization over traditional cement and lime stabilization methods. Based on a critical review of mechanical, chemical, and physical impacts, it is clear that geopolymers improve soil strength, minimize shrinkage, and increase durability, and are thus well-positioned for application in large-scale infrastructure. The comparative assessment illustrates that geopolymers have greater strength retention, long-term stability, and environmental advantages compared to conventional methods. In addition, the effect of precursor composition and curing conditions is a determining factor in performance optimization, facilitating adaptability in various soil types. Overall, the results emphasize the necessity of additional research and pilot-scale trials to optimize geopolymer formulations and their incorporation into construction activities. By overcoming current barriers, geopolymer-based stabilization can be a revolutionary method for the attainment of resilient and sustainable infrastructure development.

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