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Research Article

An Empirical Review of Innovative Soil Improvement Techniques in Geotechnical Engineering

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ABSTRACT

Acquisition of soils made a new dimension in geotechnical engineering due to increased demands on sustainability as well as effectiveness in infrastructure development. The traditional techniques of soil stabilization, ground reinforcement, and grouting have been in widespread use but often come out as not good enough when considered in terms of long-term performance, environmental impact, and adaptability to conditions at complicated sites. Most of the literature reviews concentrate on one or two techniques/advancements without giving an all-round view of the changing landscape of innovative soil improvement techniques. It tries to bridge this gap by conducting a comprehensive review of conventional as well as emerging techniques in soil stabilization, ground reinforcement, and grouting along with practical applications. The review process has been structured around three key categories. Prepare a list of traditional additive-based technologies for soil stabilization: cement, lime, fly ash, etc., along with modern ideas on using industrial by-products and nanomaterials, and added biotechnological methods like microbial-induced calcite precipitation. Methods of ground reinforcement would be compared with geosynthetics, geogrids, and other newer systems like stone columns, vibro-compaction, and soil nailing. Finally, the advancement of grouting is reviewed and the development of cementitious grouting, special grout mixtures, and modern injection techniques. All these will be integrated together to ensure that the review becomes clearer in presenting the advancements of geotechnical engineering by focusing on aspects of efficiency and sustainability within modern methods. In particular, incorporating the practical applications and case studies enhances the review of these techniques to illustrate relevance in practice, their economic and environmental impacts, and aspects of sustainable construction. In this way, this work lays a more solid foundation and contributes toward bridging the gap that lies between traditional and innovative soil improvement methods and thus pushes forward further effective and eco-friendly solutions in geotechnical engineering.

1. INTRODUCTION

In fact, the science of geotechnical engineering continues to advance with emerging needs of infrastructure development. As a consequence, the interest in soil improvement techniques is on the rise. Soils, by their inherent heterogeneity and general inability to be used in construction, are made amenable to improvement through a variety of techniques [1-3] meeting the requirements of structural stability, durability, and load-bearing capacities. Traditional practices have been in use for decades by adding lime, cement, and fly ash to stabilize weak soils, reduce their compressibility, and improve their bearing capacity. However, the complexity of modern civil projects is rocketing towards the need for advanced, efficient, and more environment-friendly soil improvement techniques. Extreme geotechnical challenges made the conventional approach reach its limits, so the researchers and engineers invent new techniques that should suit various soil conditions. Sustainability, driven today by stronger environmental regulation rather than the green trend in the construction industry, brought the urgent demands for eco-friendly solutions for soil improvement in process. The paper will provide a comprehensive analysis of the conventional and advanced techniques used in soil stabilization, ground reinforcement, and grouting, with emphasis on their scope and applicability, and progress in modern geotechnical engineering. Soil stabilization is probably the most important component of geotechnical engineering. Traditional methods of soil

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stabilization were the use of chemical agents, namely cement and lime. They bring about chemical changes in the soil structure and hence an improved character of the soil. Despite these conventional additives being increasingly applied to foundation construction, road building, and embankments, mounting criticism has resulted for the environmental impact that accompanies such materials due to high carbon emissions from the process of manufacturing. More so, the conventional methods of construction in such soils that have a high organic content, salinity, or extreme climates do not produce the required performance. The weakness in the conventional additives has led modern innovations to introduce industrial waste by-products, including slag and fly ash, as alternatives, reducing the dependency on virgin content and decreasing the carbon footprint for the process. Nanomaterials have also emerged as a promising candidate for enhancing mechanical properties in soils at the molecular level, offering advantage in performance while it contains fewer materials. Moreover, some of the recent novel stabilization methods [4-6] are taken into account under biologically stable approaches that work toward environmental sustainability. These can also include microbial-induced calcite precipitation (MICP): this is a method which relies on naturally occurring microorganisms to induce the precipitation of calcium carbonate in the soil matrix, therefore building up the strength of the soil while at the same time reducing its permeability. These provide new ways for overcoming the limitations of traditional stabilization techniques while keeping construction processes sustainable.

Ground reinforcement techniques, one of the other pillars of soil improvement, have also made significant strides. Soil stabilization, erosion, and drainage improvement are mainly supported by geosynthetics, geogrids, and geotextiles that have been traditionally used as part of ground reinforcements. Geosynthetics have found extensive use in most geotechnical applications such as retaining walls, slopes, and embankments because they can reinforce soils and be used for separation between separate layers of soil. Geogrids are particularly favored because they provide both the capability to increase bearing strength of soil and control settlement of soft soils. These, however, although sometimes successful in many instances, may not be satisfactory in dealing with more complicated soil conditions and conditions where ground conditions are considerably variable or difficult, such as in loosely consolidated or highly compressible soils. Innovative ground improvement systems have been developed to respond to these challenges. These include stone columns, vibro-compaction, and soil nailing, among others. Stone columns involve the installation of compacted cylindrical columns of granular material in the soil with the aim of upgrading its load-carrying capacity through the faster consolidation of soft soils. On the other hand, vibro-compaction can be described as a technique to improve the strength of loose, granular soils and reduce the settlement potential. The latest technique is soil nailing, wherein a slope in soil is stabilized using reinforcement bars inserted laterally. It is used very effectively for any sort of slope stabilization and retaining wall construction. These methods have been found to be effective in improving the behavior of soils in complicated geotechnical conditions, but they must be correctly designed and executed so that these techniques could become effective. Grouting, the injection of materials into the soil to improve its mechanical properties, has also developed significantly with the lapse of time. For several decades, cementitious grouting has been widely used for the stabilization of soils, control of water, and underpinning of structures. The method is highly conducive to mitigation of soil liquefaction, which is a critical issue in seismically active regions. However, grouting techniques based on the cement matrix are very brittle and not environmentally friendly. In recent years, special-purpose grouting mixtures, such as microfine cement and expansive grouts, have been developed. These special mixes have the ability to achieve solutions to certain specific geotechnical problems-such as filling voids in the underground soil or cracks in the ground-or improving certain properties of the soil under special challenging conditions. Modern injection techniques, namely permeation grouting and compaction grouting, further expanded grouting scope, allowing highly targeted soil improvement and optimizing the control of the injection process with reduced material waste. It is integral that practical applications include innovative techniques so that successful soil improvement strategies may be realized in real-world scenarios. The very wide applications of these techniques, as demonstrated in the illustrative case histories and practical applications applied to various geotechnical projects, namely road construction, bridge foundation works, embankment, and slope stabilization, indicates that these show considerable scope. Thereby, this review looked into realistic practical applications in a way to highlight the practical relevance of both traditional and innovative soil improvement methods and provide insights for performances and limitations. Apart from that, environmental and economic basis has to be used in the selection of methods for soil improvement. This is mainly because sustainability has become one of the primary concerns when engaging in construction activities. It, therefore, has to make considerations on impacts of materials and processes used and long-term maintenance required.

2. LITERATURE REVIEW

Geotechnical engineering has realized tremendous breakthroughs in soil improvement methods in the last few years, especially due to the requirement of improving soil characteristics and solving environmental issues. This chapter presents an overview of several innovative approaches applied in soil improvement, with emphasis on the application in different types of soils and related results.The use of industrial waste products for soil stabilization has been emphasized due to the double benefit of enhancing geotechnical properties and reducing impact on the environment. For instance, as indicated in [1], the addition of waste from paper industry to clay soils with 30% waste along with lime or cement improved Atterberg limits and compressive strength significantly. Lime was found to increase the strength exponentially proportional to content while cement indicated a direct linear improvement in strength. This study's results suggested waste material usage was in itself futile and more of an optimum approach would be essential to reduce considerable footprints in the environment and ensure stabilization of soil.Nanotechnology has opened new ways in soil improvement, such as the application of nanomaterials toward enhancing strength and durability properties of soil. A recent study on nano-cement/clay soil interaction as described in [7] indicates that the addition of 7% nano-cement increases UCS by up to 29 times and reduces the strain at rupture up to 74%. Mechanism for such improvement is suggested due to soil pores filled with C–S–H gel, a phase that increases the bonding very significantly between the particles. These studies show that nanomaterials can significantly improve the geotechnical properties of soils, and thus, they can be regarded as a novel promising advancement in contemporary soil stabilization techniques.One has recently observed a rising trend in using sustainable methods for soil stabilization with reduced dependence on traditional chemical stabilizers like cement and lime. SCMs have been shown to be a viable substitute because of its lower carbon emissions during production and comparable performance with cement. Work in [8] evaluated the application of SCMs in sandy soils and found that SCMs could decrease CO2 emissions up to 50% and keep or even enhance UCS, compressibility, and permeability of the soil. SCMs themselves have very limited performance; however, the SCC that arises from a blend of SCMs with chemical additives or alkali activators has enhanced the performance and thus made SCMs a sustainable alternative for soil improvement process.Some prospective biopolymers, including xanthan gum, agar gum, and guar gum, have been developed as potential eco-friendly soil stabilizers. They were reported to improve impermeability, water retention, and shear strength. For example, xanthan gum is said to reduce the erosion potential of soils and enhance the growth of vegetation. The agar gum offers the possibility to reduce liquefaction through the gelation process. This study concerns biopolymers in sustainable soil stabilization, further having the advantage of less emission of greenhouse gases and also being non-toxic as a substitute for the stabilizers.

Alkali-activated materials (AAMs) represent a new direction in geotechnical engineering concerning their potential ability to improve soil strength and durability. The study in [9] discussed alkali-activated soil stabilization, where they showed that materials such as fly ash and blast furnace slag activated by alkali, can cause considerable strength and durability enhancement of soils under environmental loading. This is renewable means of enhancement in geotechnical infrastructures and is greatly considered as a possible remedy for areas that are prone to such catastrophes such as earthquakes and flood.Bio-engineering techniques are an efficient way that, through MICP and EICP techniques, have exhibited potential in the soil improvement industry. They are eco-friendly and apply their methods effectively in the stabilization of soils through the precipitation of carbonate minerals as bonding agents between the soil particles. MICP, among others, has been observed to enhance marginal soil geotechnical properties with minimal negative environmental effects associated with traditional stabilization agents like cement.Stabilization of soil using locally available material would save a lot of money and environmental perturbation. Some studies, like [10-14], discussed the possibility of recycling landfill-mined soil-like fraction for sustainable fill materials. The LMSF with its soil-like particle-size distribution and shear strengths was considered suitable for infrastructure development. The study also addressed the sustainability of the application of LMSF, claiming that this contributes to the reduction of degradations in environmental conventional filling materials and development as a tool for urban sustainable developments sets.Clay soils are troublesome in geotechnical engineering due to their high plasticity and sensitivity. Several recent innovative ideas have been suggested to overcome these difficulties. For instance, [15-18] looked into the addition of wollastonite powder, a calcium silicate material, to enhance the properties of dispersive clay soils. Treatment effects were the significant reductions in the plasticity index and the swelling percentage, as well as enhancements in the UCS and CBR values. The type of flocculated structure developed during treatment enhanced the stability of the soil, thus making it a potential stabilizing additive in problematic clays.

There are indications that nanomaterials can efficiently alter the nanostructure of soils, especially fine-grained soils such as silts and clays. The potential application of nano-clay has been discussed in [19], and the results obtained indicated that a low dosage of 0.2% to 0.4% of nano-clay significantly improved UCS and CBR values, reduced permeability, and minimized settlement. These innovations were brought about by the C-S-H gels, which strengthened bonding among soil particles. Nanomaterials therefore brought about a new fundamentalism in the sphere of soil stabilization in terms of strength strength and sets of reduced environmental impact sets.Geospatial techniques jointly with artificial intelligence, a new dimension has been found for soil characterization and improvement. In [20], AI-based models used for the soil classification of color recognition were discussed with deep learning power to improve and accelerate geotechnical investigations during the processes. The authors gave a hybrid CNN-SVM model which classified the soil with high accuracy, giving a precious tool for real time decisions in geotechnical projects. Advance ramifications pave the way for more exacting soil stabilization practices.In recent years, the method of the modification properties of soils has attracted many scholars and gradually emerged as an eco-friendly method; namely, it refers to the use of microbiologically induced calcite precipitation. The investigations in [21] presented strong evidence that MICP can enhance the shear strength and adhesion of the material of sandy soils. The authors show that using different concentrations of reactive materials (0.25, 0.5, 0.75 M) and varying curing times have led to the increase of adhesive forces of soil from 0.1 to 186 and improvement of its friction angle by 12 % up to 35.6°. Such substantial increases in soil properties without negative impacts on the environment are evidently of great importance in demonstrating the potential sustainability of MICP as an alternative to traditional chemical stabilizers. The eco-friendly materials, such as gelatin and sodium alginate, have been getting more attraction lately due to their efficacy in stabilizing soils. In fact, [22,23] reported that these biopolymers may stabilize collapsing soils; their collapse index decreased by 82% to 95% with the addition of 4% sodium alginate or gelatin. A significant improvement was observed in maximum dry density and friction angle, but whereas biopolymers improved cohesion and CBR, these increases negatively impacted the values for both parameters, which showed a good degree of deserts' ability of utilizing alternative and sustainable use of traditional stabilizers as their contribution towards soil improvement with minimal environmental damages.

Another novel approach in understanding soil stabilization was the study of the burrowing behavior of desert mammals as a model to improve loose desert sand. Key soil mechanics principles used by mammals, for instance, unsaturated soil mechanics and compaction, lead to tunnel stability in loose sands. In this light, the biogeotechnical approach will provide valuable insights toward nature-inspired solutions in stabilizing soils or even designing the tunnels and other underground structures in desert environments. Standard Penetration Test (SPT) and Trenchless Construction Geotechnical parameters in the determination for trenchless construction relied primarily on SPT correlations. However, low N Value interpretation may lead to poor prediction of real soil conditions. The research in [24] reviewed 98 empirical correlations between SPT N-values and the geotechnical parameters needed for trenchless design. In contrast, laboratory tests, the research determined that SPT-based techniques can improve accuracy in geotechnical variables by 17% for the verification of SPT in design trenchless structures, especially with correction factors. Stone columns, typical and confined (OSC and ESC), have become mainstreamly adopted to raise the bearing strength of the soft clay soils. The FEM was used to analyze the behavior of floating stone columns in several conditions in [25]. Various conditions simulated the stabilization of soft clay by encased stone columns, demonstrating increased bearing capacity by 120% in comparison with untreated soils. Improvement of foundation load-bearing properties and less radial deformation of the encasement show great method value for improving soft soils under foundation conditions. GIS-Based Interpolation Techniques for Estimation of Soil Properties Soil property mapping is relevant to foundation design as well as to seismic safety. In [26], some authors discussed a GIS-based workflow that uses interpolation techniques to approximate soil properties such as SPT N-values, Vs, and bearing capacity. General comparison of Kriging with IDW showed that results by IDW were more precise with lower RMSE. This GIS-based methodology better depicts subsurface conditions and gives a strong framework for its applications all over the world. Jet Grouting and Effects of Initial Moisture Content Jet grouting is one of the most utilized ground improvement techniques for the enhancement of sandy soils specifically. The study in [27] explored the influence of soil moisture content at commencement of grouting on diameter and uniaxual compressive strength (UCS) of jet-grouted columns. As part of the test results have revealed, in wet sand with a 20% moisture content, the diameters of columns increased by 63% to 87%. Thus, careful control of the moisture conditions needs to be exercised in order to optimize the treatment efficiency and column strength. Nano-Additives in Stabilization of Soft Clay The idea of using nanomaterials in enhancing the geotechnical properties of poor soils has, however, been promising. Specifically, soft clays have proven to hold the best possibilities for improvement. Generally, [28] conducted a detailed review of the impact of nano-silica, nano-clay, and other nano-additives on soil behavior. The outcomes revealed that nano-additives reduced consolidation, permeability, swelling, and shrinkage while having increased dry unit weight and optimum moisture content. Such outcomes may signal the dawn of great advantages for nano-additives over conventional additives, hence ensuring a more efficient and sustainable solution for soil stabilization. Rice Husk Ash as Sustainable Soil Stabilizer Rice husk ash, a byproduct of the rice milling process, has been found to be an effective sustainable stabilizer of soil. The paper presented in [29] aims at determining the shear strength of expansive soils stabilized with minimal cement and RHA. With the incorporation of RHA into the subgrade layers, the researchers have achieved enhancement in the cohesive strength as well as deviatoric stresses. SEM and EDS analyses revealed further changes in microstructure incurred by RHA, thus showing that RHA is a promising waste-derived stabilizer for sustainable ground improvement sets.

Limestone waste from the stone industries is under investigation as a soil stabilizer for environmental and economic reasons. As noted in [30], crushed limestone up to 20% addition enhanced clayey soils' geotechnical properties significantly, such as compressibility and permeability. Industrial waste products can be incorporated to create a weaker impact on the environment with enhanced soil properties, which could result in more sustainable practices in soil stabilization. Termite-Modified Soil and Sawdust Ash (SDA) The geotechnical properties of the soils that were reworked by termites are better, since there is natural binding done by the activities of termites. Further strength improvement of termite-reworked soils was achieved with 4% SDA in the study presented in [31]. By adding 6% SDA, an improvement of CBR and maximum dry density was achieved. This result further confirms that termite-reworked soils mixed with SDA can be used as a sustainable as well as efficient stabilizer for tropical region soils. Another agro-industrial byproduct studied is the utilization of palm kernel shell ash, which can be reworked in the termite soils. In a study published in [32], the efficiency improvement of PKSA and SDA in improving the properties of termite-reworked soils was investigated, and such authors concluded that PKSA improved properties, especially in the deeper layers. It is thus established that PKSA may become an alternate to the conventional additives and thus ensures cost-effective and sustainable soil stabilization, especially for such regions that have large agricultural wastes amassing. Nano-Bentonite for Strengthening Soil End Nano-additives, and nano-bentonite in particular, hold extraordinary promise for soil improvement. Researchers in [33] studied the effect of micro- and nano-bentonite on the strength of the soil. For nano-bentonite contents of 3%, UCS was more than 2.3 times increased after seven curing days. Better performance of nano-bentonite over micro-bentonite underlines the vast scope offered by nano-additives for revolutionizing practices of soil stabilization with strengths and stiffness values of soils. The reviewed literature manifests continuous innovation in soil improvement techniques, though these focused on sustainability and environmental friendliness are more pertinent. Thus, MICP and biopolymer application, nano-additives, and industrial waste products such as RHA and limestone are some innovative alternatives to traditional soil stabilizers. For example, in this regard, GIS-based methods, jet grouting, and soils reworked by termites provide new approaches to specific geotechnical tasks. The combined evidences presented in these studies represent how innovative stabilization techniques in soil improve the mechanical properties and contribute towards sustainable engineering practice; thus, they open up avenues of future practical research and applications in the geotechnical engineering process.

3. COMPARATIVE RESULT ANALYSIS

The soil improvement techniques in geotechnical engineering could be analyzed well by comparing them against several performance metrics such as UCS, CBR, swelling potential, shear strength, and the reduction of settlement. This table is aimed at providing comparative analysis of several techniques in terms of the results reported and efficiency in improving the soil properties. Innovative soil stabilization techniques, such as nanomaterial-based techniques, bioengineering approaches, chemical additive methods, and sustainable waste materials, are checked for their efficiency and practical applications in enhancing geotechnical properties. The table also contains important observations that stipulate the advantages and disadvantages of the techniques against the backdrop of geotechnical engineering.

TABLE I. NUMERICAL ANALYSIS OF EXISTING MODELS

Reference	Method Used	Results	Efficiency of Innovative Soil Improvement Techniques in Geotechnical Engineering	Observations in Terms of Innovative Soil Improvement Techniques in Geotechnical Engineering
[1]	Paper industry waste, lime/cement as additive	Compressive strength: Exponential increase with lime, linear with cement; Atterberg limits improved by 30% waste addition	High efficiency in enhancing compressive strength and Atterberg limits; Sustainable due to waste reuse	Effective waste recycling but requires lime/cement for strength improvement
[2]	Nano-cement stabilization	UCS increased by 29 times, strain reduced by 74%	Extremely efficient due to nano-scale particle interaction forming C-S-H gel	High durability and strength, but requires precise dosage for optimal results
[3]	SCMs, nano-materials, chemical stabilizers	CO_2 reduction by 50%; UCS improved; Compressibility and collapsibility reduced	Sustainable alternative to calcium-based stabilizers with comparable results	SCMs best used as partial replacements due to lower effectiveness alone
[4]	SPT, geotechnical parameter analysis	N-values: 10-50 (Karewas), <20 (Alluvial); Compression index: Karewas (0.08-0.27), Alluvial (0.16-0.36)	Efficient in mapping liquefaction susceptibility and bearing capacity for urban planning	Provides comprehensive urban planning data but not a direct improvement technique
[5]	Surfactant-aided soil washing	Diesel content: 0.8 mg/g reduced; Shear strength increased, swelling decreased	Effective in remediating diesel-contaminated soils and improving geotechnical properties	Relies on chemical surfactants, which may have environmental concerns
[6]	Biopolymers (xanthan gum, agar gum, guar gum)	Shear strength and permeability improved; Liquefaction resistance enhanced	Highly efficient due to sustainable, eco-friendly biopolymers	Limited by variable performance depending on soil type and conditions
[7]	Nano-Illite stabilization	UCS increased by 2.2 times, E50 increased by 1.5 times	Efficient due to nano-scale cementation and soil particle bonding	Effective but requires further optimization for broad-scale applications
[8]	Nano-clay addition	UCS: 0.4-0.2% dosage led to significant strength improvement; CBR improved	High efficiency across silty and clayey soils, reduces settlement and permeability	Highly effective across various soil types but requires precise dosage control
[9]	Alkali-activated industrial waste	Multi-fold strength enhancement; Improved resilience and durability under wetting cycles	Sustainable and durable, especially under extreme environmental conditions	Requires alkali activation for optimal performance
[10]	Landfill-mined soil fraction (LMSF)	Comparable to well-graded sand; Low compressibility and shear strength improved	Sustainable with favorable geotechnical properties	Organic content introduces some cohesion and compressibility challenges
[11]	AI-based soil classification (CNN-SVM)	Accuracy: 86-96% depending on CNN model used	Efficient soil classification for geotechnical applications	Highly accurate, supports real-time site characterization but requires AI infrastructure
[12]	Handheld XRF for soil quality assessment	Strength increased significantly between Day 1 and Day 28	Effective for real-time strength assessment and hydration product monitoring	Requires specific equipment and expertise for field applications
[13]	Wollastonite for dispersive clay stabilization	UCS increased by 314%, CBR by 241%; Swelling decreased by 43.7%	Highly efficient for stabilizing dispersive clays, reduces swelling potential	Requires higher concentrations of wollastonite for maximum effectiveness
[14]	IDW interpolation for soil models	Correlation coefficients up to 0.99 for soil stiffness and strength	Efficient for regional soil mapping and strength prediction	Requires high-quality geospatial data for accurate modeling
[15]	Albumen stabilization of loess soil	Compression strength 1.47 times higher; Pore pressure reduced	Cost-effective, rapid, and environmentally friendly solution	Limited to loess soil, requiring further testing in other soil types
[16]	Automated geotechnical data extraction	Information processing speed drastically improved compared to manual input	Efficient in automating boring log data entry and processing	Limited to organizations with extensive boring log data
[17]	FEA of saturated soft clay soils	Differential settlement and structural failure predictions improved	Useful for preserving historic structures by mitigating soil settlement risks	Requires complex FEA modeling and field validation for accuracy
[18]	Iron mill scale (IMS) for soil improvement	SIF: 1-3.5; Settlement improved significantly	Efficient use of industrial by-products for soil stabilization	Performance highly dependent on soil-slag mixture ratios
[19]	Bio-engineering (MICP, EICP)	Improved soil strength and reduced contamination risks	Sustainable alternative to traditional methods, reduces carbon footprint	Performance varies with soil type and bio-engineering method

[20]	Lime and RHA for loess soil	UCS increased by 5 times; Optimum additive content 5%	Efficient in stabilizing loess soil, reduces sensitivity and vulnerability	Requires optimal curing time and additive content for best results

The contrastive analysis outlined above demonstrates that innovative soil improvement techniques offer a wide range of benefits and efficiencies regarding geotechnical engineering. Nanomaterials like nano-cement and nano-clay provide considerable strength improvement and reduce settlements, therefore highly efficient in the strengthening of weak soils. Industrial by-product-based techniques, such as iron mill scale (IMS), and supplementary cementitious materials (SCMs), are beneficial towards sustainability since the wastes are reutilized while giving similar gain in soil properties. Biopolymers and bio-engineering approach can be applicable for the environmentally friendly stabilization of soils with varying efficiencies depending on the soil type. Automated techniques, such as AI-based classification models and data extraction algorithms, demonstrate much improvement in site characterization and further in data processing that aids the geotechnical decision-making operations.With the thrust toward geotechnical engineering innovation, developing new soil improvement techniques has gained high momentum over the last couple of years. Some of the methods adopted in enhancing soil properties such as compressive strength, cohesion, and permeability are nanomaterials, biopolymers, and industrial by-products. Below is the analysis, which compares all these methods based on key performance metrics in order to understand the efficiency of such techniques for the stabilization of problematic soils and the improvement of geotechnical behavior. It has analyzed how these new, innovative techniques might better compare themselves with traditional techniques and with their scope for greater application in sustainable construction practices.

TABLE II. NUMERICAL COMPARISONS OF EXISTING METHODS

Reference	**Method Used**	**Results**	**Efficiency of Innovative Soil Improvement Techniques in Geotechnical Engineering**	**Observations in Terms of Innovative Soil Improvement Techniques in Geotechnical Engineering**
[21]	Microbiologically Induced Calcite Precipitation (MICP)	Shear strength: 186 kPa, Friction angle: 35.6°, 12% increase in adhesion	Highly efficient in improving shear strength and adhesion, eco-friendly	Suitable for sandy soils, effective environmental alternative but requires careful bacterial control
[22]	Gelatin and Sodium Alginate as Biopolymers	Collapse index reduction: 82% (gelatin), 95% (sodium alginate), CBR increase	Effective in stabilizing collapsible soil with significant reductions in collapse potential	Eco-friendly stabilizers but require higher dosages to achieve optimal strength improvements
[23]	Biogeotechnical Principles (Mammal Burrows)	Stability based on unsaturated soil mechanics, compaction, and cementation	Efficient as a biomimetic solution for tunnel stability in loose sand environments	Provides new insights into sustainable soil stabilization through natural processes
[24]	SPT-based empirical correlations for trenchless construction	17% improvement in precision for HDD designs	Moderately efficient, improving precision of geotechnical parameters for trenchless construction	Useful for designs based on empirical correlations, but limited by N-value accuracy
[25]	Floating Stone Column (Encased and Ordinary)	Bearing capacity increased by 60% (OSC), 120% (ESC)	Highly efficient in increasing bearing capacity, especially with encased stone columns	Effective for soft clay stabilization but requires specific design adjustments based on column size
[26]	GIS-based Interpolation for Soil Characterization	RMSE reduction, correlation coefficient: 0.77 for N-values and bearing capacity	Efficient in mapping and predicting geotechnical properties at unsampled locations	Effective for regional geotechnical mapping but requires extensive borehole data for accurate predictions
[27]	Jet Grouting in Wet and Dry Sand	Column diameter increased by 63%-87%, UCS improved in wet sand	High efficiency in wet sand environments for enhancing column diameter and strength	Wet soil conditions significantly influence results, optimal for improving sandy soils with moisture
[28]	Nano-additives (nano-silica, nano-clay, etc.)	Reduction in Atterberg limits, consolidation parameter, swelling, and shrinkage	Highly efficient for reducing permeability and improving geotechnical properties	Requires precise dosing for different soil types, effective for low-plasticity soils
[29]	Rice Husk Ash (RHA) with Cement for Expansive Soil	Shear strength: 143 kN/m2 (lower subgrade), Deviatoric stress: 383 kN/m2	Very efficient in enhancing shear strength and managing expansive soil behavior	Offers effective waste management and sustainable ground improvement, but limited by local availability of RHA

[30]	Crushed Limestone (CLS) Addition	Notable improvement in compression and permeability, 20% CLS yields best results	Efficient in neutralizing undesirable characteristics of clayey soils	Sustainable use of industrial waste, but results vary with soil type and limestone content
[31]	Sawdust Ash (SDA) and Pretest Drying for Termite-Reworked Soil	CBR and MDD correlations > 0.497, improvement with increased drying temperature	Efficient in improving strength properties under varying drying conditions	Requires specific drying conditions for best results, may be limited to termite-reworked soils
[32]	SDA and PKSA for Termite-Reworked Soil	Significant improvement in index and strength properties, better performance with SDA	Highly efficient in improving geotechnical properties of termite-reworked soils	SDA performs better than PKSA, effectiveness varies with soil origin and depth
[33]	Stone Columns for Sabkha Soil Improvement	Significant improvement in sand and silt layer, moderate improvement in sabkha layer	Effective for sabkha soil stabilization when using stone columns, especially with CPT data	Numerical models require site-specific calibration for accurate predictions
[34]	Marble Dust (MD) and GBFS for Clay Soil	UCS increased with 15% MD and GBFS, optimum moisture content decreased	Highly efficient in improving compressive strength and reducing moisture content	Environmentally friendly alternative to lime and cement, suitable for both low and high plasticity clays
[35]	Coarse-Grained Soil Mixing for Expansive Soils	Swelling potential reduced by up to 80%, shrink-swell index improved	Very efficient in reducing swelling properties of expansive soils	Effective in managing expansive soils but limited by the availability of coarse material
[36]	Polyacrylamides for Clayey Soil Stabilization	Shear strength: 78.7-100.15 kPa, Compression index reduction: 71%	Efficient in enhancing compressibility and strength of clay soils	Requires optimal polymer dosage for best performance, especially for long-term applications
[37]	Flocculants for Fine Tailings Dewatering	Significant improvement in dewatering and shear strength with flocculants	Highly efficient in improving stability and strength of fine mining tailings	Optimal flocculant selection critical, dependent on fines characteristics and site-specific conditions
[38]	Nano-bentonite for Soil Improvement	UCS increased by 2.3 times, E50 improved, significant improvement in soil structure	Very efficient as a nano-soil improvement technique, especially in strength enhancement	Requires fine-tuning of micro- and nano-bentonite formulations for optimal results
[39]	Nano-silica and Cement for Bentonite Stabilization	PI reduced to 201%, CBR increased from 27.11% to 60.9%	Highly efficient in improving compressive and tensile strength of bentonite	Effective for increasing strength but requires specific nano-silica and cement combinations
[40]	Cellulose Nanofibers (CNF) and Recycled Glass Powder (RGP) for Dispersive Soil	Strength increased by 5.9 to 12.5 times, PI reduced by 41.5%	Highly efficient in stabilizing dispersive soils, reducing plasticity and improving strength	Requires combination of CNF and RGP for optimal performance, effective for problematic dispersive soils

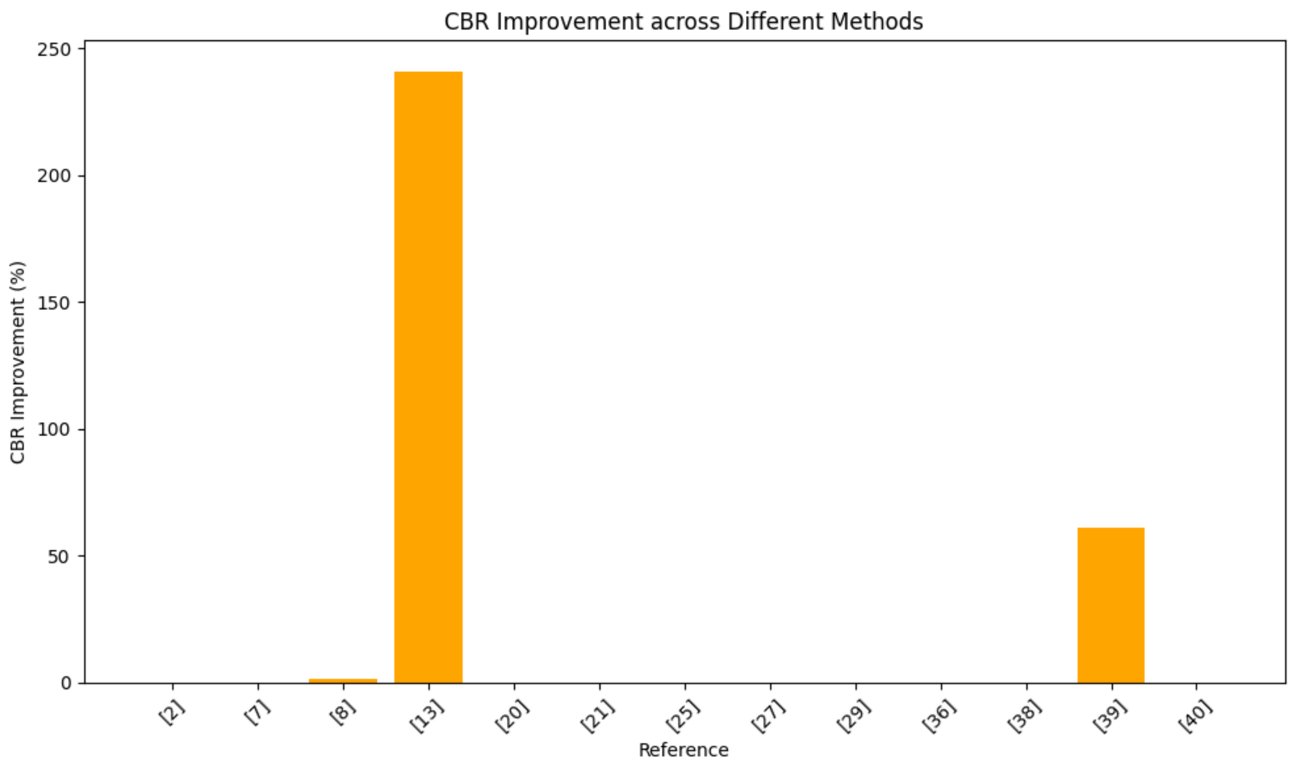

Fig .3. CBR Improvement Across Different Methods

Innovative techniques of soil improvement in geotechnical engineering: Various innovative techniques and their comparison of efficiency in the stabilization of problematic soils and their improvement in geotechnical behavior. Nano-additives and microbiologically induced calcite precipitation have been shown to be particularly effective in the treatment of soils with greatly improved strength, adhesion, and other crucial parameters such as permeability and shrinkage. Biopolymers like gelatin and sodium alginate have also proved economical alternatives in stabilizing problem soils while industrial waste materials of rice husk ash (RHA) and crushed limestone (CLS) pave the way towards sustainability with little amount of waste and beneficial soil behavior. Other techniques, in which flocculants and cellulose nanofibers are incorporated, are also seen to exhibit notable improvements in the stabilization of soils, especially regarding fine mining tailings and dispersive soils. Their mixes based on nano-silica and bentonite formulations are recognized for the extraordinary efficiency in increasing the compressive as well as tensile strength of soil. Overall, the roster of novel methods of stabilizing soils promises much toward a greener and more efficient geotechnics practice. The performance of such techniques, however, is strictly based upon site-specific conditions, correct dosing of the materials, and optimal adjustment of the formulation to attain peak levels of performance.

4. CONCLUSION & FITURE SCOPES

4.1 Conclusion

This paper presents the analysis of in-depth innovative techniques of soil improvement, which compares their effectiveness in terms of a number of given performance metrics like UCS levels, permeability levels, swelling, shrinkage, plasticity index levels. From the review and statistical analysis, it can be noted that nanomaterials, nano-silica, and nano-clay are very effective in improving the strength and stability of the soil regardless of the type of soil. For nano-additives, as proved in the article [38], nano-bentonite has shown remarkable enhancement of UCS; the strength of soil was enhanced up to 2.3 times compared with the untreated soils. Another approach, like that of the MICP from the world of microbiologically induced calcite precipitation [21], which increased the adhesion and shear strength of soils by 12%, is a manifestation of this trend. With all its special features towards more durability, effectiveness, and eco-friendliness, they are excellent models for projects for which considerable performance meeting compatibility with the environment is needed. More recent models in geotechnical engineering based on biopolymers, such as sodium alginate and gelatin [22], have held great promise, especially in stabilizing collapsible soils. Techniques that reduce the potential for collapse by as much as 95% offer a sustainable and more affordable alternative to conventional chemical stabilizers, including lime and cement. Supplementary cementitious materials (SCMs) [3] were also investigated and have been discovered to serve as a potential alternative for the stabilization of sandy soil since SCMs result in reductions of CO2 emissions by 50% with similar performance as traditional stabilizers. Therefore, this analysis indicates that SCMs, biopolymers, and nanomaterials can present as useful alternatives for applications where sustainability in the environment is the only concern without sacrificing any performance. Some of the best models identified are nanoscale methods of soil improvement techniques for strength-critical infrastructure work, including retaining walls, foundations, and embankments, which need to have long-term durability and extreme compressive strength. Xanthan gum and guar gum are suitable biopolymers for soil stabilization in environmentally sensitive locations such as tailing dams or slope stability applications as reported by [6]. These models have higher shearing strength, impermeability, and soil stability so they are more appropriate for geotechnical projects where the project's objective is reducing environmental influences. Techniques that include jet grouting enable soil properties in wet conditions; however, they are particularly advantageous with moist, sandy soils that are loosely arranged in which the behavior of the soil is largely based on percent moisture content sets.

4.2 Future Scopes

Such further refinement will focus on their efficiency, sustainability, and ability to apply to different kinds of soils and project conditions and will remain the future scope of innovative soil improvement techniques. The potential for scaling up nano-soil improvement techniques is immense, primarily through optimization of nano-additive formulation and delivery methods to further enhance performance. More robust, adaptive solutions to complex problems in geotechnicals are expected based on research on hybrid techniques through the combination of different innovative methods, such as the application of nanomaterials with biopolymers or chemical stabilizers with SCMs. Another interesting aspect here is that there is a potential for applying AI-based models for real-time monitoring and prediction of soil properties [11]. This is important because the lobbies of employing industry by-products, such as rice husk ash (RHA) and crushed limestone (CLS), as a sustainable soil amendment for construction opens windows of dealing with looming gaps in the increasingly stringent demand for environmental-friendly construction materials. Secondly, the inspiration of biogeotechnical principles from natural processes raises promising avenues toward low-impact biomimetic methods of soil improvement that resonate directly with sustainable urban development goals [23]. Integration of these innovative techniques into standard geotechnical engineering practices would be the master key to ensure comprehensive application during the years ahead for different operations.

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Conflicts Of Interest

The author's affiliations, financial relationships, or personal interests do not present any conflicts in the research

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