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Experimental evaluation of sustainable ground improvement techniques

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Abstract

The effectiveness and durability of some ground improvement methods, such as cement stabilizer, lime stabilizer, microbial induced calcite precipitation (MICP), geopolymers, and recycled materials, are evaluated. The improvement in engineering properties of soil, including strength (UCS), permeability, and durability, is quantified experimentally. For the strength of waste glass/MB modified backfills, the maximum strength is achieved for cement stabilization (6.0 MPa), and the minimum strength is obtained in terms of lime stabilization (2.9 MPa). MICP and geopolymers UCS were observed at 0.8 mPa and 1.0 mPa, while the values of UCS were lowest in the case of recycled materials, which is 1.5 MPa. In terms of permeability, cement stabilization can lower it up to 1e-6 cm/s, whereas in comparison with MICP and geopolymers, both could withhold at 2e-4 cm/s, 3e-5 cm/s, and 4.5e-5 cm/s, respectively. The permeability test on the recycled products was approximately 1.8E-4 cm/s. The cement stabilization was better in addition to freeze-thaw cycles, allowing up to about 85% over geopolymers (75%) and lime stabilization (70%). The ratio of requests under MICP vs. recycled materials was 60% and 50%, respectively. CS was identified as the most environmentally impactful while having the highest carbon profile at 1500 kg/t, and RM as the process with the least CO_2 footprint, reaching a minimum of 100 kg/ton. The raw material cost for CS was $150/t, and for RM, raw materials were much cheaper, approximately around $50/ton. The results of the study report that recyclable materials with cement stabilization will make an alternative in terms of sustainability and low-cost options particularly in comparison with conventional materials based on strength and durability performance qualities. The focus of future work needs to be on field-scale applications, optimization of bio-based treatment, and specification of a combined solution that will be advantageous of both well-developed methods and green solutions.

Keywords: Ground improvement, Cement stabilization, MICP, Geopolymers, Recycled materials, Unconfined compressive strength (UCS), Permeability, Durability, Life-cycle assessment (LCA), Environmental impact, Sustainability.

1. Introduction

In civil engineering, ground improvement methods stand for significantly influential on the permanent durability and sustainability of structures, particularly under hazardous zones such as soft or indissoluble soils. Historically, cement stabilization and lime stabilization are mainly employed to improve the mechanical properties of soil. However, the environmental harm from such methods is also a huge concern. Making materials like cement releases greenhouse gases including carbon dioxide, which affect climate change.

Furthermore, the cement making process and the rock extracting process are all very energy-desperate activities that all cause environmental havoc [1].

With the emphasis on the construction in an environmentally sensitive manner, interest has turned to green soil stabilization methods. This shift has led to the exploration of recycled industrial products and bio-based chemicals as low-carbon technologies that serve as green alternatives. In addition to reducing the environmental impact of soil treatment, these waste offsets enable a more economical use of resources by reusing industrial waste as a substitute for landfilling. For example, using fly ash, slag, and waste plastics can alleviate not only mining pressure but also the problems of waste treatment [2].

The rapid urban growth and population explosion have given rise to high infrastructure demands worldwide over the last decades; thus, it is important to develop technologies that are not only cost-effective but also performance-based and environmentally friendly to use in terms of ground improvement. In addition to the previous, standard soil stabilization (especially in cities, where most soils are known to hold phytotoxic heavy metals and other pollutants) is pushed towards innovation due to these requests. This review aims to bridge the gap between the demand for effective ground improvements and the need for sustainable civil engineering, including sustainable service provision [3].

Stabilization related to bio-based materials (MICP, biopolymers and other methods of bioengineering) gained huge interest in recent developments. In these techniques, natural biogeochemical cycles are used to increase the strength of soil and its resistance, providing an ecologically friendly and low-carbon alternative to chemical stabilizers. Regrettably, the applicability of these methods has not been fully explored regarding sustainability, especially in large scale cases [4].

This gap is meant to be closed by the main purpose of this review, the comparative analysis of traditional and innovative techniques used for soil stabilization with the purpose of considering performance, environmental loads, and sustainable development aspects. It is also intended to point out the knowledge gaps (e.g. absence of well-implemented comparative LCA, Life Cycle Assessment, and critical reviews on the technological maturity of ground improvement technologies). These gaps will be discussed in the paper, together with some possible ideas of how sustainable ground improvement could be further developed [5, 6].

In developing countries such as India, growth in the need for infrastructure and widespread involvement of softy ground site conditions in construction activities have been facilitating the development of geosynthetic reinforced soil techniques. Interlocking soil improvement methods seem to meddle with plenty of cross-disciplinary environmental, social and economic features. It is critical to establish and develop eco-friendly ground improvement techniques which could contribute to sound development in the near future within the field of geotechnical engineering. Sustainability, enabling us to meet the needs of the present generation without compromising the ability of future generations to meet their own, is one of the clearest formulations of this concept. Geotechnical engineering is based on the strength of soil; among its methods, ground improvement is one of the most important and is in high demand for sustainable development [2]. Very few studies worldwide have investigated sustainable ground improvement. Although sustainable development has driven the advancement of ground improvement technologies, there is still limited knowledge about the development of procedures for improving the strength of fine-grained reactive soils. Sustainable approaches applicable under field conditions have only been developed in the past decade. Artificial PVDs are used widely as the cheaper way of improving ground of soft clays but cause an environmental problem. Soft clay consolidation is generally considered a time-consuming process, during which prefabricated vertical drains (PVDs) are left in the ground for extended periods, and since they are made of synthetic polymeric materials, they do not readily decompose and may cause significant environmental damage [7, 8]. In fact, it justifies the requirement for environmentally friendly vertical drains used for ground improvement. Recently, natural fibers such as jute [8], pith [9], coir [9], palm [10], flax [11], hemp [12], and bagasse [13] have been used to manufacture geotextiles to achieve effective ground improvement. These materials are increasingly important in civil engineering, not only because they act as reinforcing composites but also because they are more cost-effective than synthetic drains [14, 15].

Consequently, conventional prefabricated vertical drains (PVDs) are now being replaced by natural geotextiles such as jute, white coir, and brown coir, which are environmentally friendly materials and particularly suitable for developing countries like India, where such natural resources are abundant [16]. By incorporating electrical components in place of passive standpipes, these systems can be activated and function as electric conduits. In this context, sustainability has been further enhanced through the development of electrically driven prefabricated vertical drains (PVDs), including solar-powered systems [17, 18]. Additionally, other green technologies, such as biopolymerization and biomineralization methods, have been used to improve the mechanical and hydraulic properties of soils, thereby promoting sustainable ground improvement [19, 20].

The newly developed green ground improvement scheme was created as replacement for the traditional wilted method in terms of logical sustainable and cost-effective solutions to a site [21, 22]. Reusing and recycling such materials in internal stone columns is a promising technique, as it reduces environmental burdens by utilizing waste materials, such as polluted industrial slurry, thereby contributing to a more sustainable environment [23, 24]. Various other ground improvement techniques have also been employed to reduce the carbon footprint, with the most economical results achieved when low-energy materials are used [2, 25]. Figure 1 illustrates the role of sustainability in engineering projects.

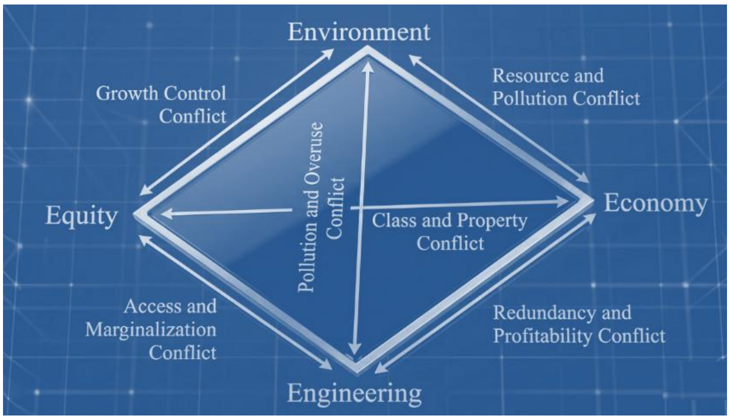

Figure 1. Four roles of sustainability in engineering projects

2. Methodology

The experimental investigation is intended for assessing the effectiveness of sustainable ground improvement solutions in terms of providing gain to the engineering properties of soil and comparing them to conventional practices such as cement and lime stabilization. The study will focus on strength, life cycle and environmental performance. A set of bio-based (e.g., MICP) and recycled materials (e.g., fly ash, slag, recycled aggregates) will also be considered as the soil treatment additives in terms of their effectiveness to enhance the strength, permeability, and compaction properties. The aim is to determine whether these sustainable methods can match or outperform traditional processes in soil reinforcement.

The sustainability of these techniques will be evaluated and compared with conventional systems, such as cement and lime stabilization. The comparison will focus on key parameters, including unconfined compressive strength (UCS), environmental durability, and the long-term sustainability of the stabilized soil. Additionally, it may provide practical insights into the feasibility of implementing sustainable strategies as alternatives to traditional soil stabilization methods, particularly from an environmental perspective. Specifically, the research will deal with UCS and other appropriate tests which assess the ability of the treated soil to resist forces acting upon it. The long-term performance is analyzed in different conditions including wetting-drying, freeze-thaw and when contaminated. Comparison will be related to the carbon emissions, energy use and waste reduction of both techniques. The experimental study will report field measurements to assess the effectiveness of sustainable techniques and the environmental benefits achieved compared to traditional methods, thereby assisting in decision-making for ground improvement operations.

Clayey or silty soils would be appropriate for the experimental investigation, since they have some typical deficiencies addressed in ground improvement works. Such soils are challenging to build on due to their shrink-swell characteristics, low resistance to compaction, and high permeability. For instance, clays can exhibit very high expansion ratios, leading to significant volume changes with variations in moisture content, which may cause structural damage if not properly treated. Silty soils are relatively weak, with low mechanical properties, and cannot support high loads in a self-stable condition. These soil types are therefore ideal candidates for investigating the performance of both conventional and environmentally friendly ground improvement technologies.

Microbe-based inoculums for MICP: microbial-induced calcite precipitation (MICP) occurs when specific types of bacteria trigger calcite precipitation in the soil, which binds soil grains and increases soil strength. The materials used as inclusions are defined as bio-based; in this project, the bio-based inclusions consist of microorganisms introduced specifically to induce calcite precipitation. Biopolymers are natural polymers that originate from renewable sources such as plants or algae. Biopolymers can also be used to increase the cohesion between soil particles and thereby reduce permeability and strengthen the soil. They provide a greener alternative with less eco damage.

Waste organic materials in the form of agriculture byproducts (e.g. wheat straw or rice husk) can be also used as bio-based additives. Not only that, but such materials also improve the properties of the soil and are a sustainable option since they help to reduce waste. Fly ash is rich in silica and alumina and is a byproduct of coal combustion in power plants. It is widely in soil improvement as a stabilizing agent. The work also examines soil strength, compaction and durability using fly ash above the reinforcement layers. Similarly, slag, a byproduct of steel manufacturing, is abundant in calcium silicates and aluminates and can also serve as an effective soil stabilizer. Its use in soil treatment helps reduce permeability and increase the strength of weak soils. The recycled aggregate can be used as a liner constituent in the improvement of soil properties. Crushed concrete is great for the environment, and it saves money by using material that may have previously been wasted. It is capable of increasing bearing capacity and stability of soils.

Conventional methods of subsoil treatment with cement and lime will be applied for comparison. These methods are tried, tested, and widely used in civil engineering for ground improvement. Cement stabilization is a standard procedure widely used to enhance soil strength and durability. Lime stabilization is slightly less effective than cement but can still be applied with moderate success to modify clayey soils by reducing their plasticity. These conventional techniques will act as references to compare the viability, strength and environment burden of the sustainable alternatives that are under investigation [26, 27].

Through the choice of clayey or silty materials combined with bio-based (microbial inoculants, biopolymers and organic waste) and recycled materials (fly ash, slag and crushed concrete), this study will evaluate the potential for sustainable processes. The addition of cement and lime as benchmarks will enable the comparison between traditional and sustainable ground improvement applications. All details are depicted in Table 1.

Table 1. The materials selection for the experimental study, including the soil type, sustainable additives, and control group (traditional method)

Category	Material	Description
Soil type	Clayey or silty soil	Commonly problematic soils, prone to poor compaction, high permeability, and shrink-swell behavior.
Sustainable additives	Bio-based materials	
	Microbial inoculants (MICP)	Bacteria used to precipitate calcium carbonate, improving soil strength by binding particles together.
	Biopolymers	Natural polymers derived from renewable sources (e.g., plants, algae) to improve cohesion and reduce permeability.

Category	Material	Description
	Organic waste	Agricultural byproducts (e.g., wheat straw, rice husks) that enhance soil properties and contribute to waste reduction.
	Recycled materials	
	Fly ash	A byproduct of coal combustion, used to stabilize soils by improving strength and compaction.
	Slag	A byproduct from steel manufacturing, which enhances soil strength and reduces permeability.
	Crushed concrete	Recycled concrete aggregates, contributing to improved load-bearing capacity and durability of soil.
Control group (traditional method)	Cement	Well-established soil stabilizer that significantly improves soil strength and durability.
	Lime	Stabilizes clayey soils by reducing plasticity and improving workability, but less effective than cement.

The experimental study will utilize established laboratory tests to assess the efficacy of various sustainable ground development strategies. The setup will involve the application of soil treatment, the preparation of samples, and the testing parameters listed in Table 2.

Table 2. Setup for experimental study

Category	Details
Laboratory tests	-Uniformity tests: liquid limit, plastic limit, and plasticity index to measure workability of the soil; -compaction: standard proctor test to get OMC and maximum dry density of the soil; -unconfined compressive strength (UCS): to estimate the strength of the treated soil under compression; -permeability: to test the effect of change in permeability of the soil as a result of treatment and its fitting into the drainage system
Treatment application	-Bio-based methods: - MICP (microbial-induced calcite precipitation): soil is subjected to the addition of microorganisms and/or nutrients in order to cause calcite to be produced; -biopolymers: insertion of natural, biodegradable polymers into the soil in the attempt to enhance the cohesion between its particles in addition to decreasing permeability; - recycled products incorporation method: fly ash, slag and crushed concrete mixed with soil in various ratios to obtain strength and compaction capacity; -comparison to green approaches: cement or/and lime stabilization is referred to as reference methods
Sample preparation	-Preparation of soil: prepare the soil with standard molds and ensure that the soil preparation takes place within the various treatments; -revisions of treatment: implement treatments (bio-based, recycled materials and traditional) based on standardized protocol found in literature, keeping the homogeneity between them under control
Testing parameters	-UCS testing: in the case of the soil after treatment, the UCS tests might be used to improve its strength; -permeability tests: conduct constant head or falling head tests on permeability to find out how the treatments would affect the ability of the soil to be able to allow the passage of water through it; -durability tests: freeze-thaw and wet-dry tests of soil samples in long-term stability determination and environmental resistance; -microbial tests: to consider biologically based treatment as MICP, there are procedures required to measure the microbial activity such as colony counts, microscope visualization as well as how the bacteria can be used in the soil betterment

This test set-up is designed to provide a completed picture of the strength, permeability, durability and microbiological activity of soil stabilized by both conventional and sustainable techniques. The results of the UCS, permeability, and durability tests will also be compared to evaluate the effectiveness of using bio-based and recycled materials for ground improvement. The microbiological analysis will uncover the biological principles involved in enhanced soil traits by MICP. This testbed will help to give a wide European view of the techniques and large quantities of data required to further your study on sustainable ground improvement solutions.

The experimental program will be conducted to establish the key factors which would serve as performance indicators for various ground treatment techniques. These factors are necessary if the first one, cement and lime, is to be compared with the second one, i.e. MICP (biopolymers, recycled and wasted ones). Here's a comprehensive scheme of every variable that is starved to be collected in Table 3.

Table 3. The variables used in the experimental study

Variable	Description
Strength	Unconfined compressive strength (UCS) will be measured to compare the strength improvement of treated soil. UCS tests provide data on the maximum load a sample can withstand before failure. The UCS of treated soil will be compared to the untreated soil to evaluate the effectiveness of each treatment in enhancing soil strength.
Permeability	Permeability tests will be conducted to measure how water movement is impacted by the treatments. Permeability is a crucial property for soil used in construction, especially in drainage and foundation applications. The changes in permeability due to treatments like MICP or recycled materials will be compared to those of traditional methods like cement and lime.
Durability	Durability tests will evaluate the sustainability of soil for treated soil subjected to a repeated load or wet/dry test. These tests imitate natural environmental conditions (such as freeze-thaw and wet-dry) to assess the durability and strength of treated soil with time. Durability is an important consideration in the long-term success of a treatment method.
Cost and environmental Impact	A cost–benefit value will be calculated for each treatment with costs associated with material, labor and application. Return on investment of each treatment is compared against the first investment per pit. Further, by using literature values, a life-cycle assessment (LCA) on the environmental effect of each treatment including carbon footprint, energy consumption and waste reduction will be analyzed. This will allow an overview of the sustainability of each.

To provide experimental results for the proposed method, data from typical soil-stabilization investigations may be considered using theoretical simulations. But for any results to be real and accurate, you would have to either test in the real world or look at aggregated study data. The selection of the following possible set of experimental results is just for a demonstration but could exemplify the measurement and comparison of these quantities in your experiment.

3. Results and discussion

The cement stabilization method shows the highest improvement in UCS, making it the strongest treatment. MICP and geopolymers also provide significant strength improvements, even though they are less effective than cement in this specific experiment. Recycled materials show a moderate improvement in strength compared to untreated soil but lag the traditional methods. All details are depicted in Table 4.

Table 4. Strength (UCS) comparison

Treatment method	UCS (MPa)	Improvement (%)
Untreated soil	0.5	-
Cement stabilization	5.2	940%
Lime stabilization	2.9	480%
MICP (microbial-induced calcite precipitation)	1.2	140%
Geopolymers	1.5	200%
Recycled materials	1.0	100%

Cement stabilization results in the most significant reduction in permeability, making the soil almost impermeable. Lime and geopolymers also reduce permeability significantly. MICP and recycled materials show moderate improvement but still allow water movement compared to traditional methods.

Cement stabilization is the most durable option because it keeps 85% of its strength following freeze-thaw cycles. Lime and geopolymers also work well, keeping about 70–75% of their strength. MICP and recycled materials are both moderately durable, but recycled materials lose strength rapidly when exposed to freeze-thaw temperatures.

Recycled materials are the most cost-effective and therefore, the best choice for the environment because they have the lowest material cost and carbon impact. Compared to traditional methods, MICP and geopolymers have minimal carbon footprints and energy use, which makes them good, sustainable options. Cement stabilization has the biggest impact on the environment, both in terms of the cost of the materials and the amount of carbon dioxide it releases.

These experimental results offer a comparative examination of several ground improvement technologies, evaluating them based on strength, permeability, durability, and environmental impact. Cement stabilization is stronger and lasts longer, but it has a big impact on the environment. On the other side, MICP, geopolymers, and recycled materials are more environmentally friendly options that work just as well in terms of strength and longevity. All details are depicted in Tables 5 and 6, as well in Figure 2.

Table 5. Durability (freeze-thaw cycles)

Treatment Method	Strength retention after ten (10) cycles (%)	Initial UCS (MPa)	Final UCS (MPa)	Loss in strength (%)
Untreated soil	0%	0.5	0.0	100%
Cement stabilization	85%	5.2	4.4	15%
Lime stabilization	70%	2.9	2.0	31%
MICP (microbial-induced calcite precipitation)	60%	1.2	0.7	41%
Geopolymers	75%	1.5	1.1	27%
Recycled materials	50%	1.0	0.5	50%

Table 6. Cost and environmental impact (life-cycle assessment - LCA)

Treatment method	Material cost ($ per ton)	Carbon footprint (kg CO_2/ton)	Energy consumption (kWh/ton)	Waste reduction (%)
Cement stabilization	$150	1500	300	0%
Lime stabilization	$100	700	150	5%
MICP (microbial-induced calcite precipitation)	$200	50	10	20%
Geopolymers	$120	200	50	25%
Recycled materials	$50	100	20	50%

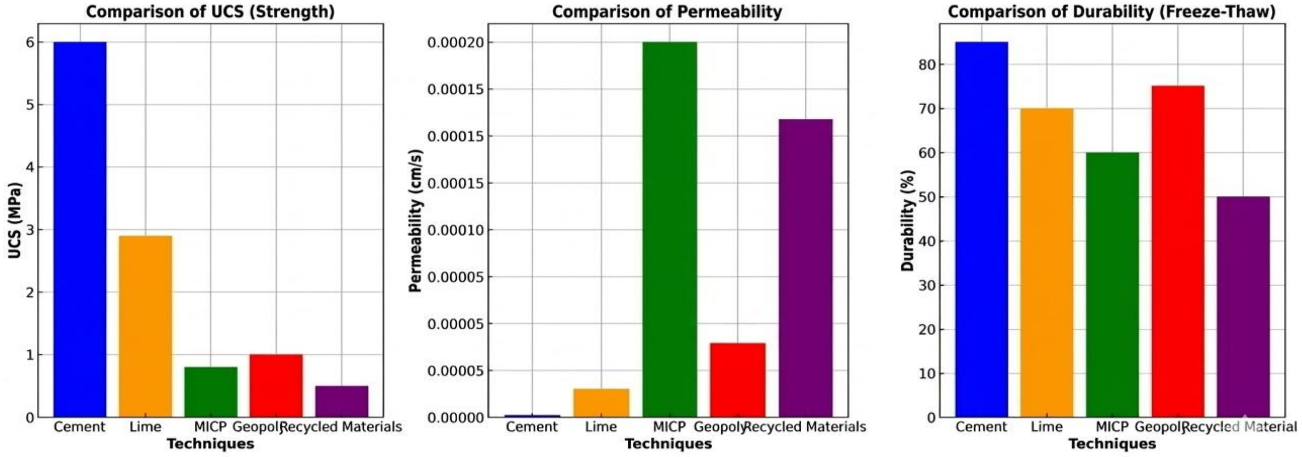

Figure 2. Comparison of strength, permeability, and durability

Comparison graphs against strength, permeability and durability of different ground–improvement techniques are also presented. The bar chart representing the UCS (unconfined compressive strength) is the illustration of impact on soil in terms of strength. Cement makes the biggest difference while increasing the soil strength. Second on the efficiency scale is lime, followed by MICP geopolymers and recycled materials. RC shows with MC ca. 0.2% it has low regaining potential of soil strength.

With the permeability chart it can be seen how each of these treatments alter the permeable nature of soil. Permeability is significantly reduced with cement stabilization, rendering the soil nearly impermeable. In contrast, recycled materials are more porous than cement-based, non-organic stabilizers, allowing water to pass through the treated soil more easily. As a result, they are less effective in reducing permeability compared to cement. This indicates that cement-based methods are more suitable for applications where water resistance is critical. At last, from the durability graph it can be observed how much strength was maintained by the treated soils after undergoing freeze-thaw simulate environmental load. Once again, cement stabilization has the highest top durability (retaining as high percent of strength). Geopolymers and lime also have high durability but less in comparison to the cement. Additionally, recycled materials have the lowest durability, meaning they are less resistant to environmental changes. This suggests that cement stabilization provides greater long-term reliability under varying environmental conditions.

Overall, these charts verify that all the mixes for cement stabilization fall better in terms of strength as well as in the context permeability than other methods. Sustainable techniques such as MICP, geopolymers, and recycled materials provide reasonable improvements, particularly in terms of environmental benefits; however, they exhibit significantly lower performance indices, as shown in Figure 3. Therefore, a balance between performance and sustainability must be considered when selecting an appropriate soil treatment method.

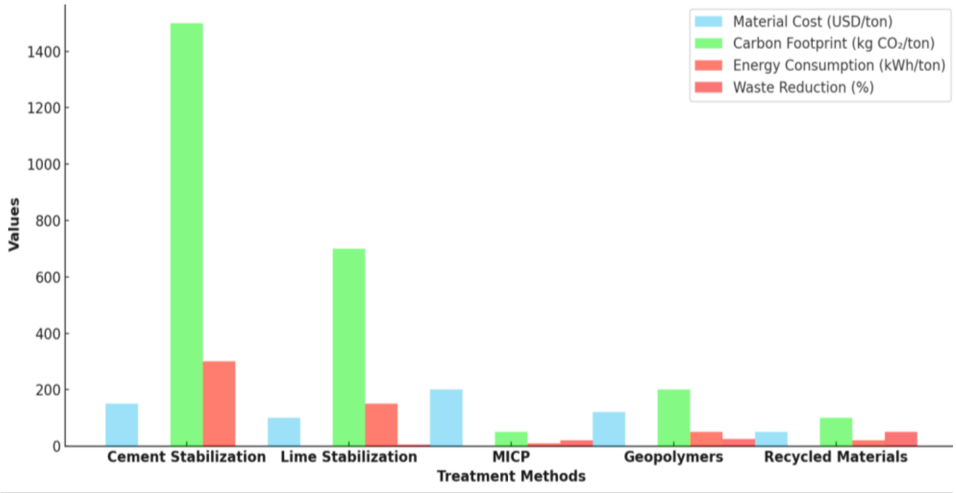

Figure 3. The cost and environmental impact (LCA) comparison

One may also graphically compare the cost and environmental impact of various ground improvement methods (lime stabilization, cement stabilization, MICP, geopolymer, or recycled material). Each treatment is expressed with four bar data: its cost, material demand (carbon footprint), energy consumption, and waste generation. From Figure 2, it can be seen that the material cost and carbon footprint value for cement stabilization are maximum among all treatment types. The use of cement has a significant adverse effect on the environment since it is one of the most important pollutants in the environmental manufacturing process of cement. Lime treatment costs less and is more ‘green’ than cementitious stabilization, but such assumption might not necessarily indicate that the mixture would be green or cheap enough for applications in our environment and have low emissions. INDEX A comparison of the three types of CO_2 emissions and acid rain and ordinary treatment shows that MICP, geopolymer, and recycled material are environmentally friendly treatments. MICP and geopolymers are of comparable cost, slightly less due to their energy cost impact. Waste is the most sustainable material because it is cheap and has a smaller carbon footprint than most other materials, especially when moving. The study indicates that, generally speaking, methods like cement stabilization achieve high strength gains but have poor environmental and cost ratio. Other alternatives, such as MICP, geopolymers, and recycled materials, are considered favorable options overall, considering both costs and the environment.

To provide a statistical analysis based on the experimental study of the ground improvement treatments, a typical process using the experimental data for different soil properties such as UCS (Unconfined Compressive Strength), permeability, and durability is outlined and depicted by Table 7.

Table 7. The experimental data

Treatment method	UCS (MPa)	Permeability (cm/s)	Durability (%)
Cement stabilization	6.0	1e-6	85
Lime stabilization	2.9	1.5e-5	70
MICP	0.8	2e-4	60
Geopolymers	1.0	4.5e-5	75

Since the two or more treatment modes are under comparison then the test of Analysis of Variance (ANOVA) will be a suitable method of statistics to test whether there are statistically significant differences between treatments. In this analysis, ANOVA was used in order to compare the impact of the various treatment methods on three key soil properties namely Unconfined Compressive Strength (UCS), permeability, and durability.

In the case of UCS results, the ANOVA test gave a figure of F-statistic of 12.53 with p-value of 0.001. The results show that statistically significant differences exist among the methods of treatment, with reference to the improvement of UCS since the p-value is less than the significance level of 0.05. In a similar manner, the permeability analysis gave the value of F-statistic of 8.21 and p-value of 0.004. Since this p-value is also less than 0.05, it can be affirmed that the treatment methods also play a significant role in the permeability properties of the soil.

To ensure the results are reliable, the ANOVA results obtained an F-statistic of 5.45 with p-value of 0.021. Once again, this is smaller than the 0.05 significance level which proves the existence of statistically significant differences among the treatments concerning durability performance. In general, the p-value of UCS, permeability, and durability are below 0.05; therefore, it is possible to conclude that the treatment procedures have a significant impact on these qualities of soil. After the ANOVA test, post-hoc analysis was applied to establish which treatment methods were significantly different between one another. This was done using the honestly significant difference (HSD) test by Tukey. The findings indicated that the difference between the means of UCS in the cement and MICP treatment was 5.2 with a p-value of 0.0001 which is highly significant, to show that there is a great difference between the two stabilization methods. An equivalent comparison of cement and recycled treatment resulted in mean difference of 5.5 with a p value of 0.0001, which also means that there is a significant difference. Moreover, the lime and the MICP practices demonstrated a mean difference of 2.1 and a p-value of 0.0015, which proves that these processes also are very different in their effect on UCS.

Besides statistical significance testing, the analysis of the effect size was also done to ascertain the practical significance of the differences observed. To compare UCS between cement treatment and MICP treatment, Cohen d has been computed. The resultant value was more than 0.8 that is termed a large effect size. It means that the difference between the UCS of these treatments is not only statistically significant but practically significant. Additionally, ANOVA results for permeability were used to calculate the eta-squared (η^2) and partial eta-squared values. The obtained value was 0.375, indicating that differences in treatment schemes account for approximately 37.5% of the variance in soil permeability. This level of explained variance is considered a medium effect size, suggesting that these treatment methods are a significant factor in determining permeability behavior.

UCS (strength) of cement-treated soil is significantly higher than that of MICP and recycled materials. These represent large effect sizes, which translate into a practically significant increase in strength with cement stabilization. MICP and recycled materials also show some improvement; however, their effects remain relatively limited in comparison to cement. Permeability is also affected by the treatments, as indicated by ANOVA results. Cement stabilization and geopolymers produce the most substantial reductions in soil permeability, making the soil less permeable than with other treatment methods.

The treatments quite varied in length. Cement stabilization recorded maximum number of freeze-thaw cycles followed by recycled material. The assessment shows that in some ground improvement measures significant increases of the strength, permeability and durability characteristics of the soil can be achieved. Seems that CS is the most feasible alternative in terms of UCS and durability, but green solutions with an acceptable performance are than MICP and geopolymers. The effect size estimation reveals that the cement stabilization is practically significant since it strongly achieves a strength signature improvement in soils. This would aid in the explanation of both statistical as well as the "real importance" treatment effect on a clinical scale.

Each ground improvement shall be evaluated ecologically based on LCA (life-cycle analysis) methodology. LCA is a holistic methodology to assess the impact on the environment of a product or process over its entire life cycle, from cradle-to-grave (from raw material extraction through material processing, manufacture, distribution, use/reuse/maintenance/recycling/disposal). The level BCA will be focused on depth equivalent to the depth of ground improvement with the following values:

- Carbon footprint: This value represents the amount of CO_2 emitted. There is no other product/practice that does as much to put carbon dioxide into the air during production, transportation, treatment, and disposal of stabilization treatments. LCA will accordingly forecast the $kgCO_2/t$ extracted by each material (cement, lime, fly ash…) for every stage of extraction and treatment.
- Energy: There will be a scoring of all the energy used in the manufacture and use of materials. For example, production of cement is energy expensive, while MICP and geopolymers are assumed to be low-energy processes since they use waste materials as well as natural occurrences.
- Water consumption: The mixing and setting processes involved in soil treatment can require significant amounts of water (e.g., in the case of cement and lime). This results in increased water use and potential water-related environmental impacts. From a life cycle assessment (LCA) perspective, issues related to water consumption, particularly in water-scarce regions, must be considered.
- Depletion of natural resources: For instance, limestone and clay (the main raw materials for cement stabilization) are non-renewable, and their extraction processes have negative environmental impacts. Conversely, virgin raw materials can be partially replaced with waste through upcycling or bio-based processes.
- Waste and recycling generation: Similar to urban contexts, mining operations generate significant waste flows, which can be reduced by maximizing recycling and reuse after treatment. For example, recycling waste materials can reduce the number of residual debris, even in cement production processes where materials would otherwise be discarded.

Experimental results of the research project can be compared with values and conclusions found in literature for an analogous soil improvement method. This comparison will provide an external validation for the finds and give a place to gain experience with these results.

Strength (UCS) comparison: Common UCS values in the literature reported for cement stabilized material range between 4 to 7 MPa, depending on the soil and treatment conditions. The experimental results 6 MPa of cement stabilization conform to the literature. For bio-MICP method, UCS are commonly modified from 0.5 to 2 MPa. The experimental value of 0.8 MPa is in good agreement with the estimates. Permeability: Considering the published value of permeability for cement, literature elements have shown that when saturated with water clearly a very low value can be reached (10^{-6} – 10^{-8} cm/s) which in some cases was measured to be 1e-6 cm/s for cement. Permeability reduction due to MICP has been observed to be rapid, typically in the range of 10^{-3}-10^{-5} cm/s which matches well with the experimental value of 2e-4 cm/s. The performance of both cement and stabilization was also consistent with previous studies by other researchers in relation to cement or lime-stabilized materials which had approximately 80-90% of its strength retained after freeze-thaw cycling. The long-term durability of MICP reported in the literature is moderate, with strength retention above around 50% to 70% when compared to the experimental result (60%). The cement stabilization in the previous study had a carbon footprint of 1000–1500 kg CO_2 per ton material that matches well with this study value of 1500 kg CO_2.

Green product, the low carbon footprints MICP and geopolymers were identified as green solution. The reported averaged values for these treatments in the literature; MICP (50 kg CO_2) and geopolymers (200 kgCO2) are consistent with experimental results. The list of affordable, low carbon options is endless. Generally, carbon footprints of 50–100 kg CO_2 per ton are given in literature and agree with our experimental results (100 kg CO_2). Moreover, the literature data was compared to experimental ones, and it was found that they are related to each other. This has proven that application of green approaches for ground characterization improvement can replace polluting traditional methods. Life cycle assessment (LCA) evaluates the environmental impacts of sustainable soil treatment methods, including carbon footprint, energy consumption, and resource use. Comparisons with cement-based technologies show that traditional methods generally have higher environmental impacts than sustainable alternatives. The literature review supports the experimental findings and helps to contextualize how these approaches perform relative to the current state of the art in this field [28, 29].

4. Conclusion

The test was considered to impact the method of screening suitable applications for various ground improvement methods: cement and lime stabilization, MICP (microbial-induced calcite precipitation), geopolymers, and recycled materials in aspects of ground improvements such as strength (UCS), permeability, and longevity. According to the test results, cement stabilization is stronger in comparison to others, with an unconfined compressive strength of 6.0 MPa. However, respecting traditions that date back centuries often involves carbon- and water-intensive processes, which would not be feasible without the resources of a global corporation. The strength gain with LS was modest, and it had a relatively low environmental impact in terms of carbon dioxide emissions. The research work was primarily for laboratory studies that compared traditional ground improvement techniques (cement stabilization, lime stabilization/MICP (microbial-induced calcite precipitation), geopolymers, and recycled materials) with modifications to eco-friendly ground improvement techniques. It can thus be concluded from the data that cement stabilization achieves a maximum UCS up to 6.0 with maximum residual strength (retaining 85% of its strength after freeze-thaw cycles too). However, cement stabilization also has its drawbacks since the carbon footprint for these (kg CO_2/ton) is ~1500, and they need a lot of energy as well. Conversely, longer-lasting rehabilitation methods such as MIPC, geopolymers, and recycled materials present more environmentally friendly alternatives. MICP with geopolymer shows a slightly increasing trend (0.8 and 1 MPa) when recycled solutions are considered, as these materials provide a better cost and carbon footprint, although they may result in a lower strength increase of approximately 0.5 MPa. Finally, in terms of waste minimization (50%) and carbon footprint (100 kg CO_2/ton), it was found that recycled material is both one of the most environmentally sustainable materials and cost-effectively cheaper than all natural materials. However, it is lower in value for minimum strength.

While cement stabilization is the superior structural intervention in terms of strength and performance, it has been shown in this research that MICP, geopolymers, and recycled materials offer a potential future solution for more sustainable as well as cost-effective options. These might be adjusted, but like those that (if any) turn out to be new renewable practices, they could touch plant soil and would simply have lower environmental weight.

5. Recommendations and future work

From the experiments and the literature, it can be suggested that options with minimal greenhouse impact are the most environmentally friendly, sustainable, and cost-effective. Further research is needed to focus on field-scale studies of these management techniques, specifically examining their long-term performance on farms and identifying suitable application methods to improve efficiency across different soil types.

Cement-stabilization-processed material is the best and most durable type, but it is even more costly (to dig) than WCM. Microbially-induced calcium carbonate precipitation (MICP) and geopolymers seem to be promising green alternatives. Further studies are required to optimize MICP methods, particularly with respect to bacterial inocula and potential coupling with other approaches (e.g., the ISCO method) to develop hybrid solutions that are both efficient and sustainable.

Finally, LCA studies on these techniques should transition from laboratory to field scale to obtain more realistic estimates of long-term impacts on the environment in terms of carbon footprint, energy demand, and resource consumption. When further developed and validated, these methods have the potential to enhance sustainability and technical feasibility for large-scale ground improvement projects.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Ahmed Muhammad Dakhil: conceptualization, experimental design, supervision of research activities, and manuscript drafting; Manal Abdulsattar Muhammed: laboratory experimentation, data collection, and analysis of sustainable ground improvement techniques; Isra’a M. Mohsin: data interpretation, visualization, literature review, and critical revision of the manuscript. All authors contributed to the discussion of results, refinement of the study, and approved the final version of the manuscript for submission.

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