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Issues and Challenges of Sustainability in Soft Ground Construction

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Abstract

Soft ground construction often presents significant challenges, such as low bearing capacity, high compressibility, and a high susceptibility to settlement. These geotechnical issues can lead to instability, costly maintenance, and safety concerns if not addressed appropriately. In recent years, attention has increasingly shifted towards incorporating sustainable materials and innovative construction techniques to address these problems more effectively while minimizing environmental impacts. This paper reviews and analyzes three sustainable approaches in geotechnical applications for soft soils: the use of recycled materials, the implementation of geosynthetics, and the application of microbial-induced calcite precipitation (MICP) techniques. Recycled materials, including industrial by-products such as steel slag and fly ash, offer an eco-friendly alternative to conventional fill, reducing waste disposal while improving soil strength. Geosynthetics, including geotextiles, geogrids, and geomembranes, provide reinforcement, separation, and drainage functions, thereby enhancing stability and service life. MICP, a bio-mediated ground improvement technique, promotes calcite precipitation within soil pores, increasing stiffness and reducing permeability without relying on conventional cement-based binders. In addition to these sustainability-focused approaches, this review presents a comparative assessment of three case studies addressing embankment construction over soft ground. The first case study examines wick drains and counterweight fills at Salamanga, Mozambique, for accelerated consolidation and stability improvement. The second investigates geosynthetic reinforcement combined with floating pile walls in Egypt, highlighting settlement reduction and economic savings through optimized design. The third explores lightweight fill materials and preloading techniques for shallow soil strata in urban environments. A critical comparison of these methods is provided in terms of feasibility, applicability, cost-effectiveness, geotechnical performance, and environmental sustainability. The paper concludes with practical insights and recommendations for integrating sustainable solutions into soft ground construction, offering valuable guidance for future infrastructure projects in challenging soil conditions.

Keywords: Sustainability, Geosynthetics, Recycled Materials, Microbial-Induced Calcite Precipitation (MICP)

Introduction

Geotechnical engineering plays a crucial role in construction projects, particularly in areas with soft ground conditions. Soft soils, characterized by high water content, low shear strength and poor bearing capacity pose significant challenges to infrastructure development [1]. Conventional soil treatment approaches, such as stabilization with cementitious binders, have been widely used. However, these approaches have been found to contribute to high greenhouse gas emissions, driving the need for better sustainable and eco-friendly alternatives [2]. This report explores the potential of innovative materials and techniques for addressing the issues and challenges associated with construction in soft ground. By reviewing three approaches: recycled materials, geosynthetics and microbial-induced calcite precipitation (MICP), this report aims to identify the most effective and sustainable solutions for addressing soft soil challenges.

Problem Statement

Soft ground conditions, often characterized by high water content and low shear strength, lead to problems like settlement, instability, and foundation failures. Conventional methods such as replacing soil or chemical stabilization are resource-intensive and can harm the environment. Sustainable alternatives are essential to improve soil properties while minimizing ecological impact and ensuring cost-effectiveness. This report evaluates several sustainable techniques to address these challenges effectively.

Methodology

A qualitative research approach is used to analyse and compare three sustainable techniques for soft ground construction. Data from academic journals. Case studies and industry reports are examined to assess each method's feasibility, efficiency, cost, and environmental impact. Evaluation criteria include:

1. Feasibility: How practical the method is for real-world applications.
2. Cost: Initial and long-term economic implications.
3. Efficiency: Effectiveness in improving soil properties.
4. Sustainability: Environmental benefits, including resource conservation and reduced carbon footprint.

Related Works

Recycled Materials for Soil Stabilization

Application: Recycled materials like fly ash, copper slag, and crushed concrete improve soil strength and reduce settlement. Feasibility: Easy to source in regions with abundant industrial by-products. Cost: Economical due to the use of waste materials, though processing and transport may add cists. Efficiency: Enhances soil properties effectively, though performance varies based on material quality. Sustainability: Reduces waste and reliance on non-renewable resources.

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Case study 1: This study investigates the utilization of industrial waste materials including silica fume, cement kiln dust, calcium carbide residue, rice husk ash, and ground granulated blast furnace slag, as eco-friendly stabilizers for expansive clay soil (Figure 1). The laboratory findings demonstrate that these additives significantly enhanced the soil's physical, mechanical, and microstructural properties, resulting in reduced liquid limit, plasticity index, and swell potential, while simultaneously increasing unconfined compressive strength and shear strength (Figure 2). The results suggest that these industrial waste materials can serve as effective and sustainable alternatives to traditional soil stabilization techniques.

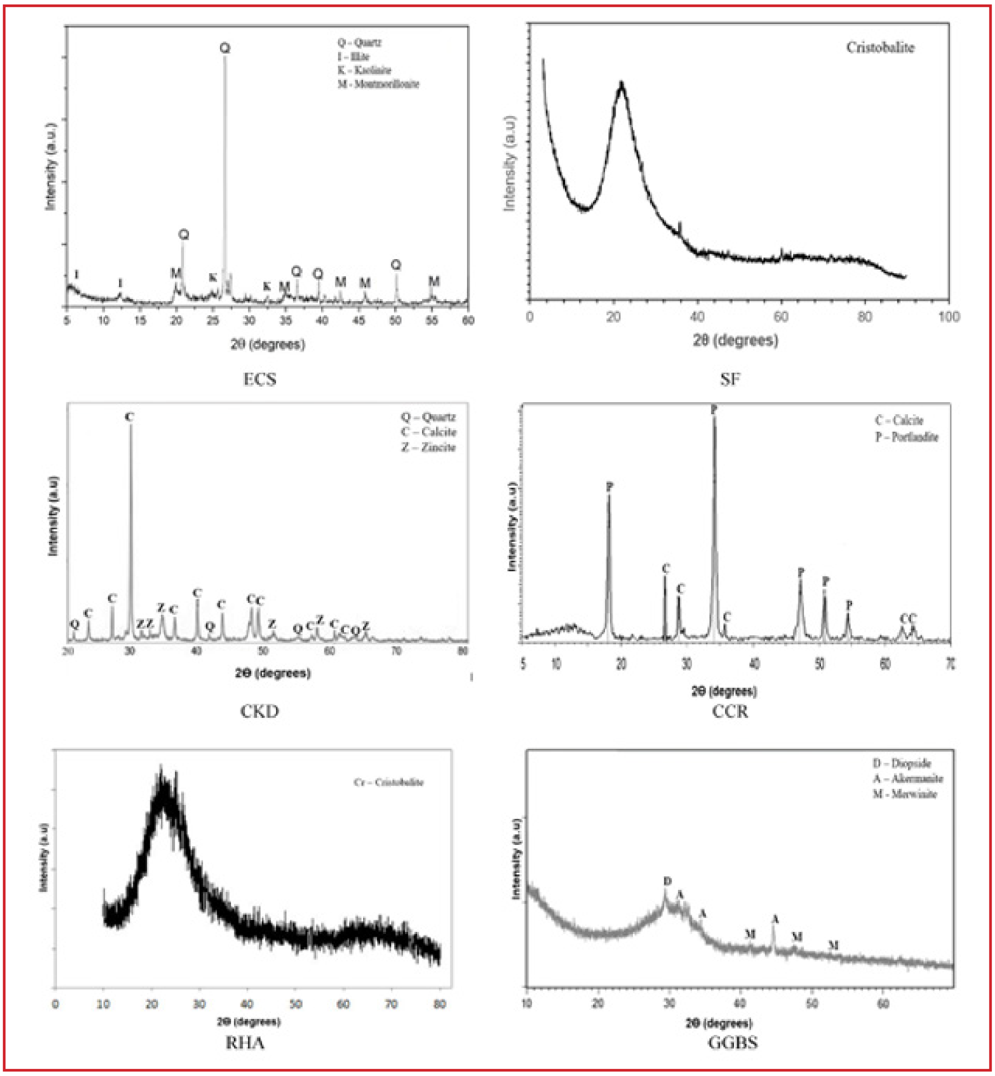

Figure 1. Mineralogical XRD pattern of expansive clay soil (ECS), silica fume (SF), cement kiln dust (CKD), calcium carbide residue (CCR), rice husk ash (RHA), and ground granulated blast furnace slag (GGBS).

In a laboratory study testing various industrial waste additives (cement kiln dust and etc) at 3%, 6% and 9% proportions on virgin expansive clay soil (ECS), the plasticity index (PI) decreased, indicating improved soil stability with ECS-GGBS showing the most significant reduction, 74.76% [3].

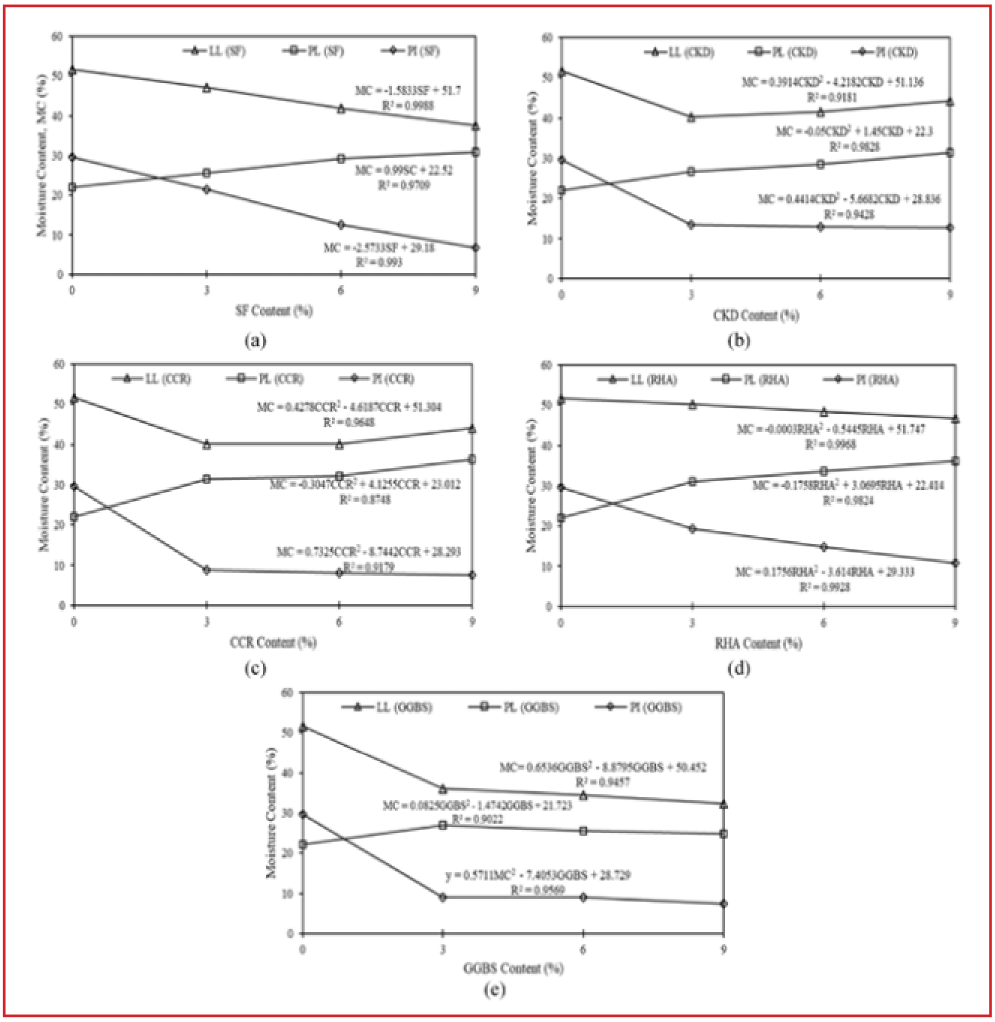

Figure 2. Plasticity of ECS improved with (a) SF (b) CKD (c) CCR (d) RHA and (e) GGBS content.

Case study 2: Recycled waste tires, as shown in Figure 3, have shown great potential in geotechnical engineering applications such as subgrade backfilling and slope reinforcement. Comprehensive evaluations of the engineering characteristics and environmental impacts of these recycled waste tire-soil/ sand mixtures have revealed favourable performance in terms of compression, deformation, shearing, dynamic, and thermal/microstructural properties.

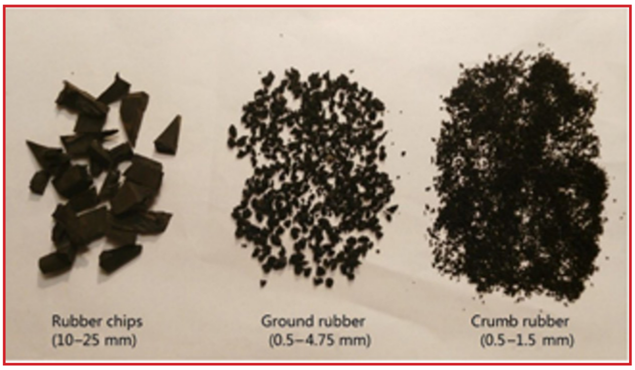

Figure 3. Designation of waste tires rubber tire particles in current South Australian market

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As illustrated in Figure 4, Edil and Bosscher [4] reported that tire debris–sand mixtures possess greater strength compared to pure sand, with denser mixtures showing stronger shear strength. Foose found that the initial friction angle of sand-tire mixtures could be twice that of dense sand. Tatlisoz [5] found that shear strength increased with tire chip fractions up to 30%, as shown in Figure 5.

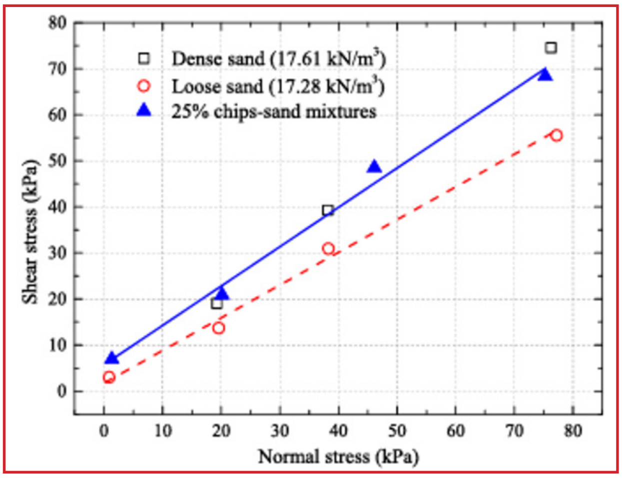

Figure 4. Shear strength of pure Portage sand under 25:75 tire chips Portage sand mixture [4]

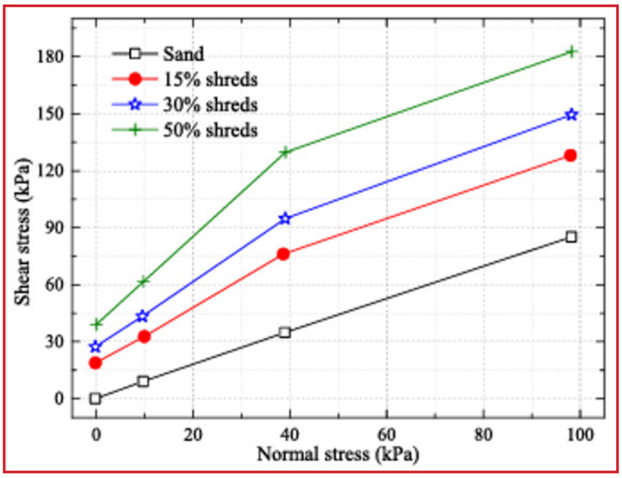

Figure 5. Variation of shear stress with normal stress on samples with 4 x 8 cm shreds at γ_w= 16.8 kN/m [5]

Case study 3: In Perlis, Malaysia, fly ash was utilized for soil stabilization as a sustainable alternative to Ordinary Portland Cement (OPC), achieving a 3-day unconfined compressive strength (UCS) exceeding 0.8 Mpa with a geopolymer mixture containing 20% fly ash and a FA/AA ratio of 2.0, meeting the Malaysian Public Work Department’s guidelines for road subgrade construction [6].

Case study 4: In Baghdad, recycled crushed concrete from demolished buildings was used as an alternative to non-renewable gravel from natural resources, achieving an increase of 40-145% of undrained shear strength and a reduction in the compression index by 25 - 47%. [7].

Geosynthetics

Application: Geotextiles, geogrids, and geomembranes are widely used for soil reinforcement and drainage. Feasibility: Versatile and suitable for many soft ground scenarios. Cost: Moderate initial investment but offers durable solutions Efficiency: Distributes loads evenly and reduces settlement effectively Sustainability: Environmentally friendly in use, though synthetic production impacts its eco-friendliness.

Case study 1: This research investigates the influence of horizontal geogrid reinforcement on the load-carrying capacity and deformation characteristics of floating and end-bearing granular piles installed in soft clay soils. Through a combination of laboratory testing and numerical modelling, the study compared the performance of reinforced and unreinforced piles.

Based on Figure 6, the results showed that for granular piles with geogrid reinforcement at 25-, 50-, and 70-mm c/c spacing, the ultimate load intensity increased by 442%, 396%, and 316%, respectively, compared to untreated ground using laboratory model tests and numerical analyses. Additionally, incorporating geogrid strips reduced bulging, enhancing the stability of the granular piles [8].

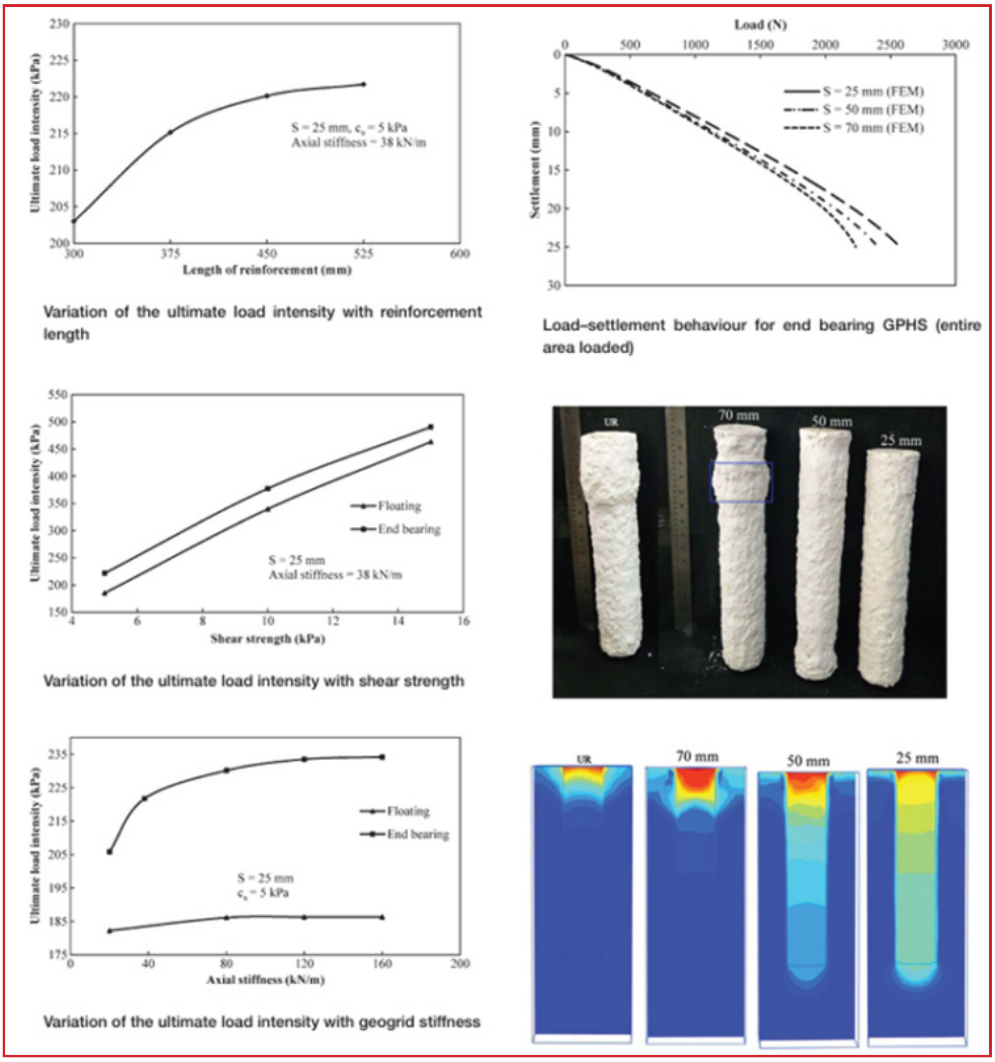

Figure 6. Ultimate load intensity variation for different distributions

Case study 2: Studies have shown that geosynthetic materials like geocell can improve subgrade bearing characteristics, reduce deformation and enhance stability. Field tests and numerical simulations indicate significant improvements in load-bearing capacity and surface deflection when using geocell-reinforced soft rock subgrades. Figure 7 illustrates the cross-sectional diagrams of the soft rock subgrade reinforcement treatment plans.

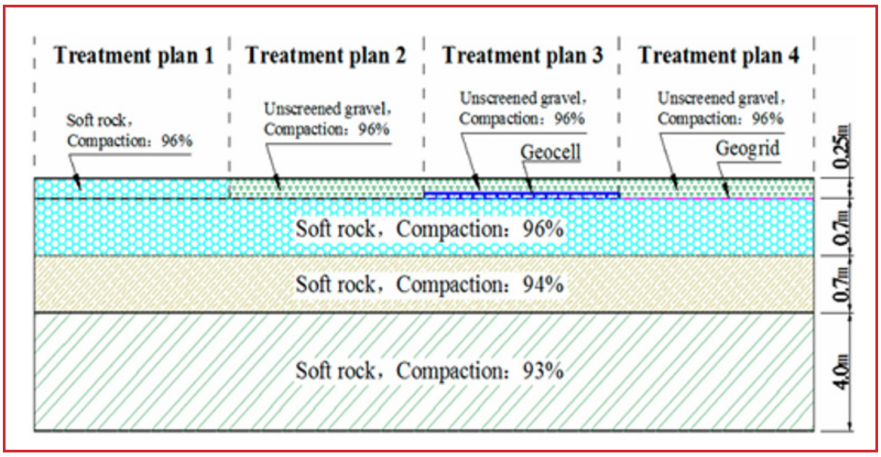

Figure 7. Cross-section diagrams of the soft rock subgrade reinforcement treatment plans.

Field tests and numerical simulations on geosynthetic materials for treating the soft rock subgrade show that by implementing unscreened gravel and geocell (treatment plan 3) yields the best results (Figure 8). This plan significantly reduces penetration, increases the converted CBR by 46%, and enhances the dynamic deformation modulus by 27%. It also reduces peak dynamic soil pressure by 30.1% to 37.2% and improves the subgrade's stiffness, resistance to deformation, and surface deflection under vehicle loads [9].

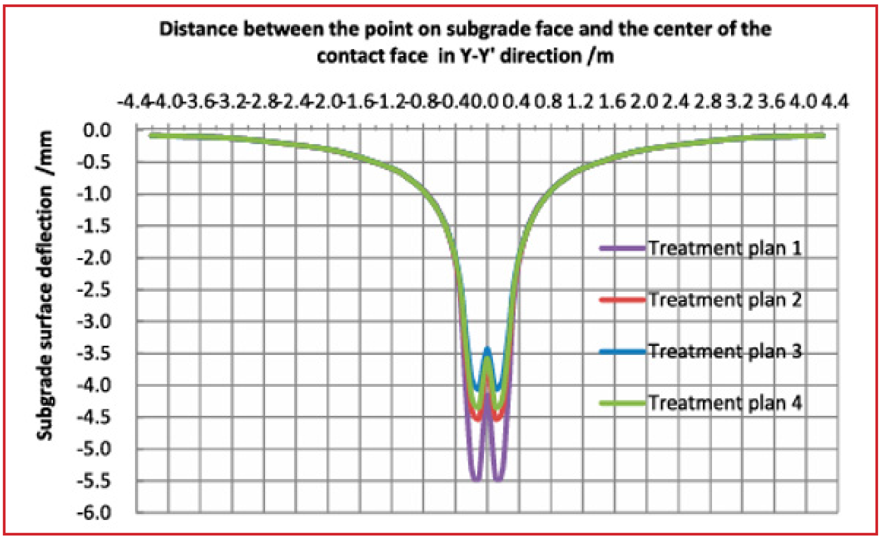

Figure 8. Subgrade surface deflection distribution in the Y-Y' direction under the vehicle with full load

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Case study 3: Reinforcing tunnels with geogrid significantly reduces deformation and stress, ensuring long-term safety and stability, with deformation ratios in Iraq decreasing from 0.15mm to 0.09mm [10].

Case study 4: The use of geogrid and geotextile in road construction project in South Africa demonstrated a 17% reduction in soil settlement for geogrid, 23% for geotextile and 31% for the geogrid-geotextile combination [11].

Microbial Induced Calcite Precipitation (MICP)

Application: MICP can be applied in construction foundations due to its ability to stabilize loose soils. Figure 9 shows the soil specimens used in this case study. This technique is suitable for roadway, embankment, and shallow foundation applications. In addition, MICP can also be utilized to stabilize seabed soils in coastal areas or at the foundations of underwater pipelines.

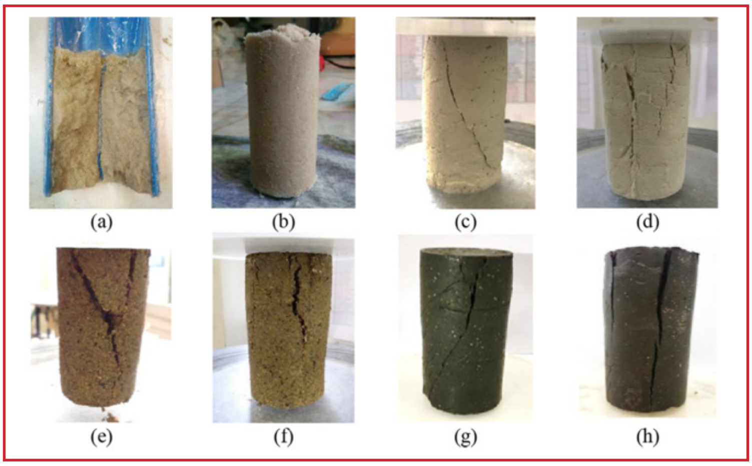

Figure 9. Soil specimens used in this case study

Feasibility: MICP proven to increase the compressible strength and reduce the permeability in soil. It is also cheaper in term of logistic where it is not necessary to transporting large construction materials. On the long run, MICP treated soil have high durability and reduce maintenance costs.

Cost: It is cost effective and sustainable solution compared to various waste media. The use of more local resources as waste materials can reduce transport costs.

Efficiency: The calcite precipitation rate is a major influence in the efficiency of MICP method. Utilization of resources efficiently ensure this method is proven to be cost effective and reduces environmental impact.

Sustainability: MICP uses less quantities of cement with the replacement of bacteria, calcium resources and urea. It has low carbon footprint compared to other cement-based method where the process relies on biological processes heavily. The need for worker to handle heavy machinery and hazardous cement chemicals reduces significantly with the use of MICP thus making a safer working condition.

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Case study 1: This study is about the effectiveness of MICP and choosing the suitable chemical conditions. The results showing that the nutrient proved that the bacteria can be used in the precipitation of calcite. The essential nutrients required for MICP could not infiltrate into high-plasticity clayey soil, resulting in a low level of MICP activity and limited improvement in soil strength properties [12]. Figure 10 shows the stress–strain results of the soil specimens obtained from the unconfined compression test.

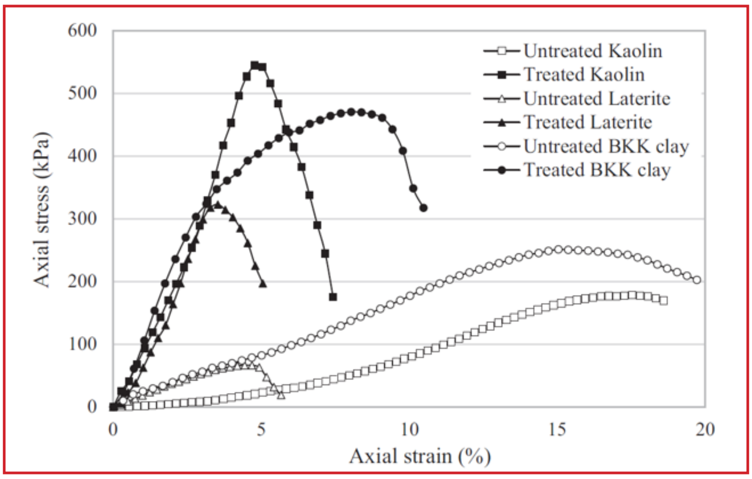

Figure 10. Soil specimen stress-strain result for unconfined compression test

Case study 2: This research examines three case studies on the application of MICP in pavement works, including assessments of construction costs and environmental impacts. The findings show that soil permeability decreases significantly with an increase in $CaCO_3$ content. However, the use of MICP in subgrade composition also results in higher construction costs and increased CO_2 emissions [13]. Figure 11 presents examples of untreated and treated soils based on both experimental and modelling results.

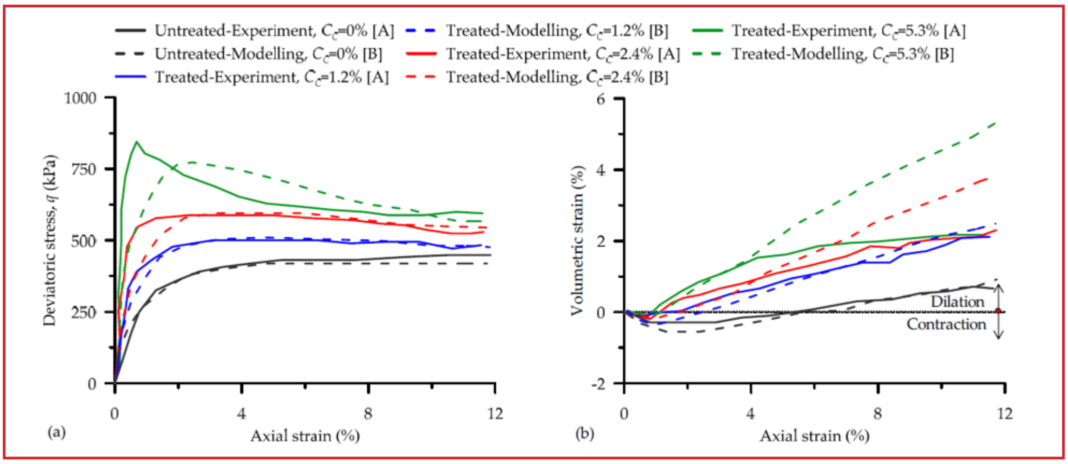

Figure 11. The comparison between untreated and treated soils obtained from both experimental and modelling results.

Case study 3: The Sporosarcina pasteurii bacteria solutions were used to mix with soft clay specimens with variety of nutrients concentration. From Table 1, the results indicate that MICP is a feasible solution for enhancing the strength of soft clay through the direct mixing of the bacterial solution with the clay and nutrient salts [14].

Table 1. Compressive strength of 28d for unconfined soft clay specimens

Specimen no.	Nutrient concentration (mol/L)	Relative $CaCO_3$ content (%)	Average $CaCO_3$ content (%)	Stress (kPa)	Average stress (kPa)
0.00 a	0.00	—	—	20.29	17.89
0.00 b	0.00	—		15.48	
0.50 a	0.50	2.7	2.3	44.94	43.31
0.50 b	0.50	1.8		41.67	
0.75 a	0.75	2.8	2.5	30.30	28.89
0.75 b	0.75	2.2		27.47	
1.00 a	1.00	3.5	2.7	31.11	30.19
1.00 b	1.00	1.8		29.26	

Comparative Analysis

Recycled Materials: As illustrated in Figure 12, recycled materials are both cost-effective and environmentally friendly, helping to reduce waste and conserve natural resources; however, variability in their material properties can present certain challenges [15,16].

Geosynthetics: Geosynthetics are effective and widely used for soil reinforcement and erosion control, with high initial costs justified by their durability, long-term benefits, and contribution to sustainability by reducing the need for traditional construction materials.

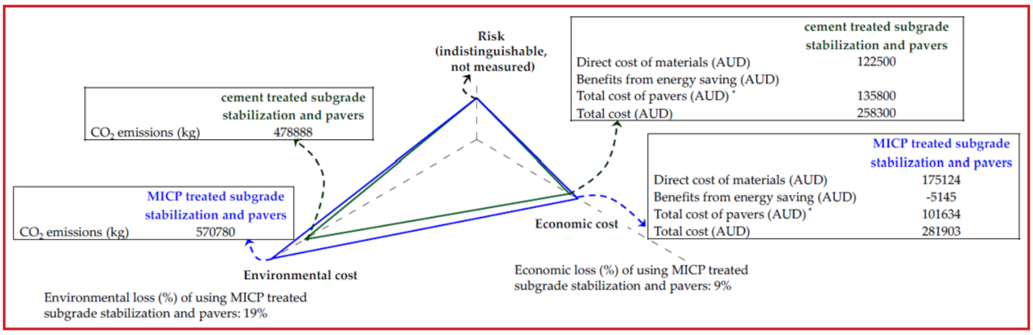

Figure 12. General direct material cost of MICP-treated and cement-treated materials

Table 2. Comparative evaluation of recycled materials, geosynthetics, and MICP methods based on feasibility, cost, and efficiency

Method	Feasibility	Applications	Cost	Efficiency
Recycled Materials	High	Ground improvement, lightweight fills	Low	Environmental friendly
Geosynthetics	High	Versatile, roadways, embankments	Moderate	Durable, immediate results
Microbial Induced Calcite Precipitation (MICP)	Medium	Roadways, embankment and shallow foundation	High	High workability and environmental friendly

Microbial Induced Calcite Precipitation (MICP): In terms of workability, it is one of the easy methods to do and safer option when it comes to materials and equipment handling. The cost is slightly high when compared to other methods, as this technology still new in the industry. There is possibility for this technology to be explored in depth [17-19]. Table 2 summary of the feasibility, applications, cost, and efficiency of various ground improvement methods.

Opinion And Discussion

Each method offers unique benefits and challenges. In our view, geosynthetics stand out as the most practical and versatile solution for addressing soft ground related challenges. Their adaptability, cost-effectiveness, and established performance position them as fundamental component of sustainable geotechnical practices. Recycled materials provide an excellent complementary option, particularly for projects with budget constraints or a focus on waste reduction. MICP has a great potential in the geotechnical field for its ability to improve the soil engineering properties. Due to its complexity in soil microbiology and soil chemical components not all soils are suitable to the same type of MICP treatment condition. So, it is important that the selection of bacteria is crucial to make MICP method works better. Besides that, the surrounding temperature and condition of microbial diversity shall be taken into account as it impacts the bacteria survival. Ultimately, implementing a variety of innovative approaches customized to project specific conditions will be crucial to achieve truly sustainable soft ground construction.

Conclusion

The construction industry plays a crucial role in addressing the global challenge of sustainability. The findings of this research suggest that these alternative materials and techniques can effectively improve the mechanical properties of soft soils, while mitigating the environmental impact associated with conventional cement-based solutions.

In our opinion, geosynthetics stand out as the most effective and sustainable solution for soft ground construction. Their balance of cost, efficiency and environmental benefits makes them a versatile and reliable choice. Recycled materials are highly commendable for their cost-effectiveness and contribution to waste reduction. As for the MICP, this method still new in the industry and there are many improvements to be done before it can be widely used and to be a more cost-effective method. Moreover, with the use of MICP there will be a need to do monitoring work to control soil pH value during treatment, this further add to the operation cost.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Fatin Hamizah Samni: investigation, methodology. **Dinesh Gunasegar:** validation, data curation. **Dayang Zulaika Abang Hasbollah:** writing- original draft preparation, supervision. **Bakhtiar Affandy Othman:** writing- reviewing and editing.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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