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# A Study on Alternative Low-Emission Sustainable Soil Stabilization Techniques in General and Combat Military Operations

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## Abstract

This paper explores the applications and benefits of innovative soil stabilization technologies—such as Microbially Induced Calcite Precipitation (MICP), biopolymers, and geopolymers—that are both effective and environmentally sustainable, particularly in the development of temporary and permanent infrastructure during military operations. The study emphasizes their sustainability, rapid deployment, and enhanced durability, and how these technologies offer significant advantages for constructing and maintaining defense infrastructure compared to conventional techniques and materials. By analyzing comparative data, case studies, and environmental impacts, the potential of these materials to transform military operations is assessed.

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## 1. Introduction

Militaries globally are significant carbon emitters, yet comprehensive data on their emissions remains elusive due to varying levels of transparency and operational contexts [1]. The environmental impact of military operations extends to infrastructure development, where the use of concrete for fortifications, such as blast walls, notably increases the carbon footprint. An LCA of US forces' use of blast walls in Baghdad (2003-2008) exemplifies this issue [2]. Furthermore, the

Indian Army's infrastructure in Jammu & Kashmir alone reportedly emits over 60,000 MT of CO2 annually[3]. Figure 1 depicts a comparison of carbon dioxide emissions in 2019 between China, the United States, India, the global military, Russia, and Japan. China leads in emissions, while Japan has the least, and the global military's carbon footprint falls between India and Russia. The data presented accounts solely for $CO_2$ emissions, not carbon equivalents ($CO_2e$) [4].

Cement, essential in military infrastructure for its durability, contributes significantly to carbon emissions, being responsible for 7-8% of global CO2 emissions [5]. Yet, it's critical for constructing airfield pavements, bunkers, and the like. In seeking sustainable alternatives, this paper explores soil stabilization methods—MICP, biopolymers, and geopolymers—aiming to enhance military operational capabilities while mitigating environmental impact [6][7][8]. These methods offer competitive strength and durability with lower carbon emissions, especially beneficial in ecologically sensitive areas [9][10].

The paper further discusses the scope and comparative effectiveness of these methods within the defense sector, positioning them as viable substitutes to traditional cement in defense-related construction, against the backdrop of military $CO_2$ emissions, with China and the US leading and the global military also contributing significantly.

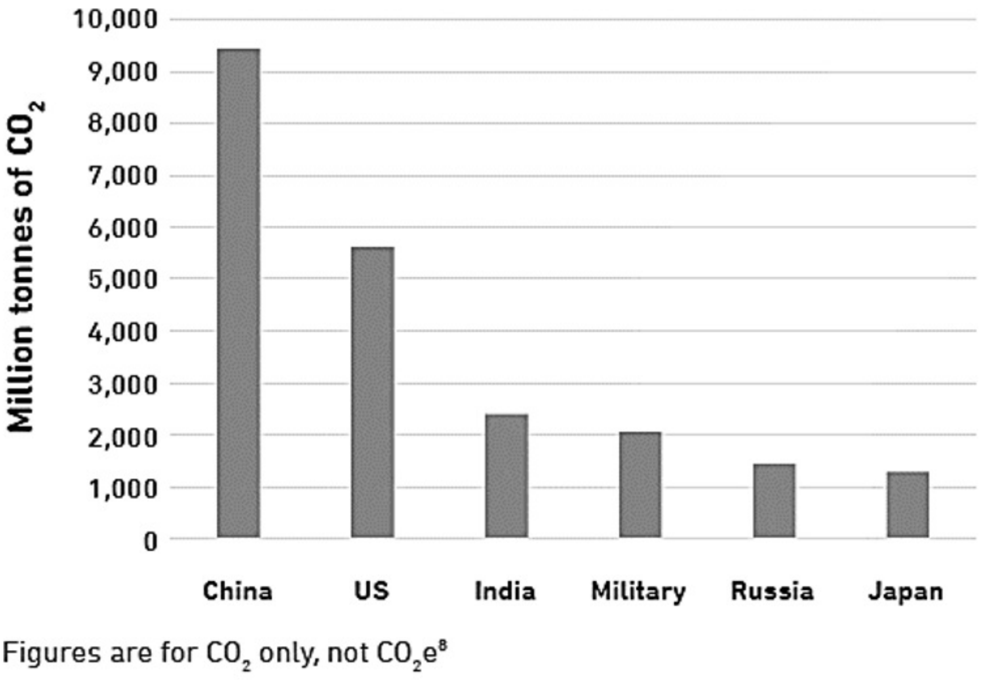

**Figure 1.** Global military carbon footprint compared with top five nations 2019 (Source: Parkinson S, 2023)

## 2. Low Emmison and Sustainable Soil Stabilization Techniques

### 2.1. Microbially Induced Calcite Precipitation (MICP)

Microbially Induced Calcite Precipitation (MICP) is an innovative bio-geochemical process that employs ureolytic bacteria to stabilize soil through the precipitation of calcium carbonate [11]. The core chemical reaction involves the hydrolysis of urea, catalyzed by the enzyme urease produced by the bacteria. This reaction is represented by the equation:

$$CO\left(NH_2\right)_2 + 2H_2O \rightarrow \left(NH_2\right)_2CO_3$$

The breakdown of urea increases the pH and the concentration of carbonate ions, leading to the formation of calcium carbonate when these ions react with available calcium ions in the environment, as shown by the reaction:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \text{ (solid)}$$

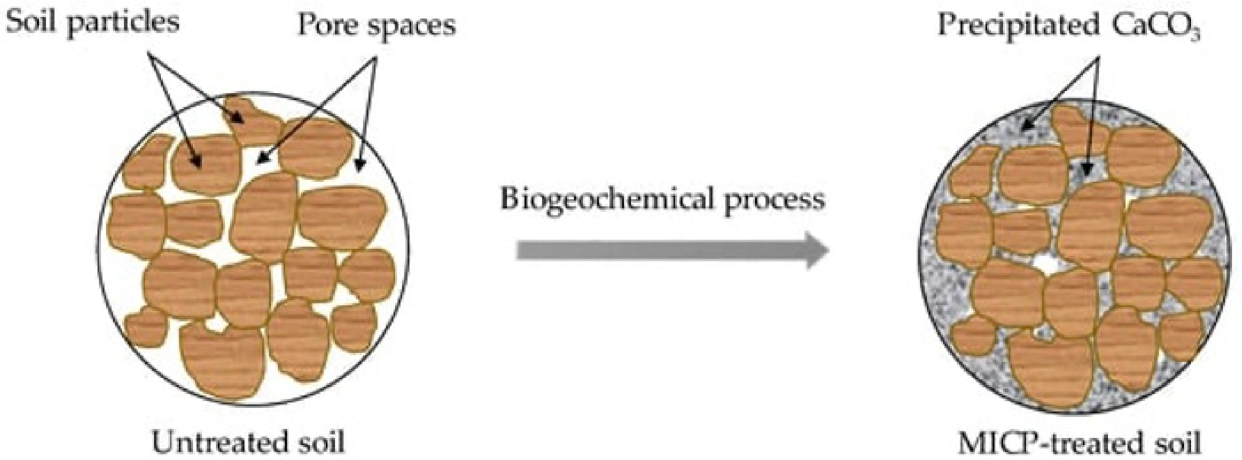

**Figure 2.** A schematic diagram of $CaCO_3$ precipitation in the pore space of the soil matrix via MICP. (Rahman, M.M et al. 2020)

The MICP method boosts soil strength and erosion resistance while being more eco-friendly than conventional cement stabilization. It's less energy-demanding and may help sequester CO2. Figure 2 from Rahman, M.M. et al. 2020 shows MICP filling soil pores with $CaCO_3$, thus reinforcing soil[12].

## 2.2. Using Biopolymers

Biopolymers, derived from natural and renewable sources like xanthan gum, starch-based polymers, and cellulose derivatives such as carboxymethyl cellulose (CMC), are gaining recognition for sustainable soil stabilization. These materials form hydrogels that absorb water and expand, effectively binding soil particles and enhancing structural integrity. Applied as a slurry, biopolymers facilitate easy, even distribution and are environmentally favorable due to their biodegradability and low carbon footprint. However, their performance can vary with environmental conditions, necessitating adaptations to local climates and soils. The development of biopolymer formulations continues to improve their effectiveness in soil stabilization projects. Figure 3, from G. Cho and I. Chang in 2018, shows a month-long time-lapse study demonstrating the efficacy of biopolymer treatment in maintaining soil stability and controlling erosion across different slope sections, with marked soil erosion observed in the untreated area [13].

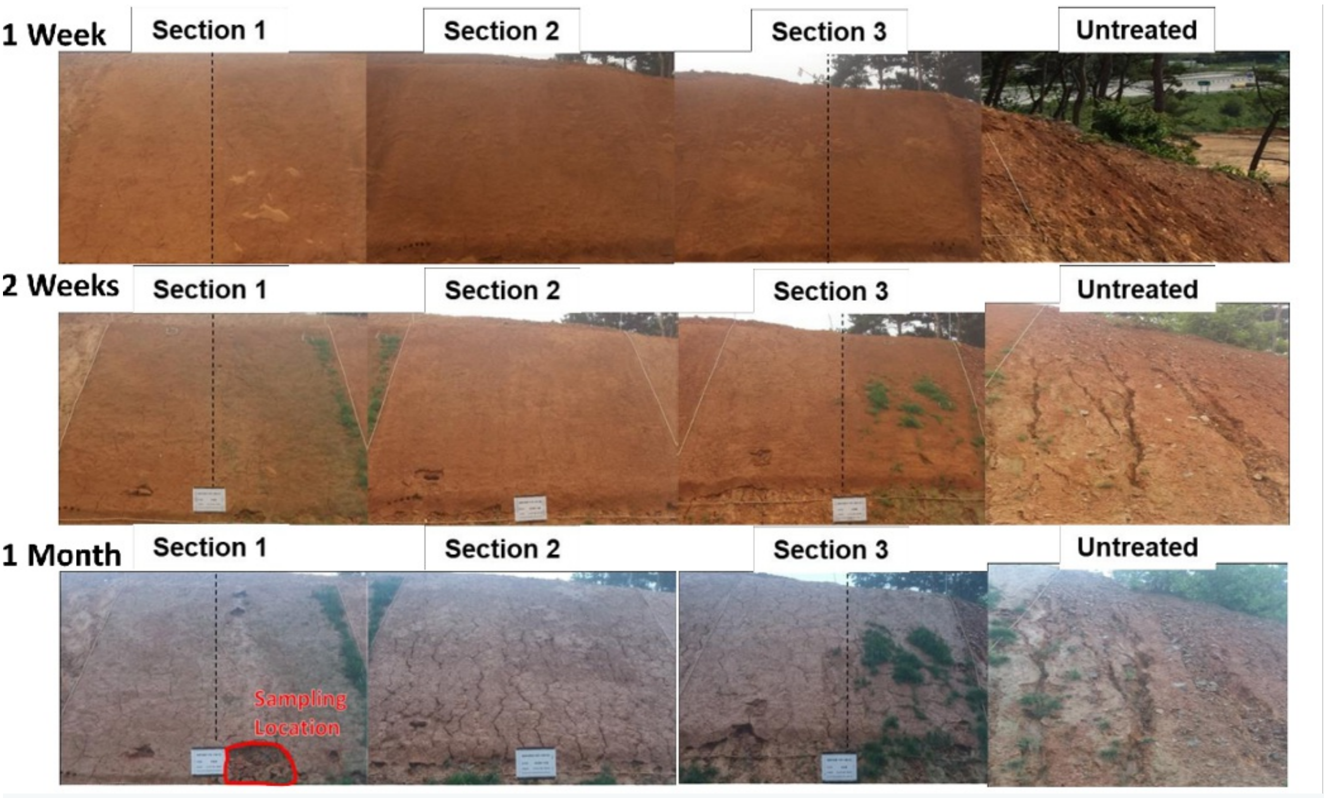

**Figure 3.** Slope treated with biopolymer (Source: G. Cho, I. Chang 2018)

## 2.3. Using Geopolymers

Geopolymers, derived from aluminosilicate materials like fly ash or slag, are advanced inorganic polymers that react with alkaline solutions to effectively stabilize soils[6]. This reaction forms a ceramic-like matrix that enhances soil strength, reduces permeability, and provides excellent resistance to chemical and thermal stresses. Valued for their environmental benefits, geopolymers utilize industrial by-products and bypass the high-temperature processes required for traditional cement, significantly cutting carbon emissions. Their rapid curing and strong bonding properties make them suitable for urgent and durable soil stabilization in diverse engineering projects, promoting sustainable construction by leveraging waste materials and minimizing maintenance needs. Figure 4, referenced from Pooia Ghadir et al. 2021, provides a schematic overview of stress distribution in soil, the influence of confinement on shear surface development, and the comparative effectiveness of different binders like geopolymer and cement under various curing conditions, illustrating the mechanics of soil stabilization and enhancing soil strength [14].

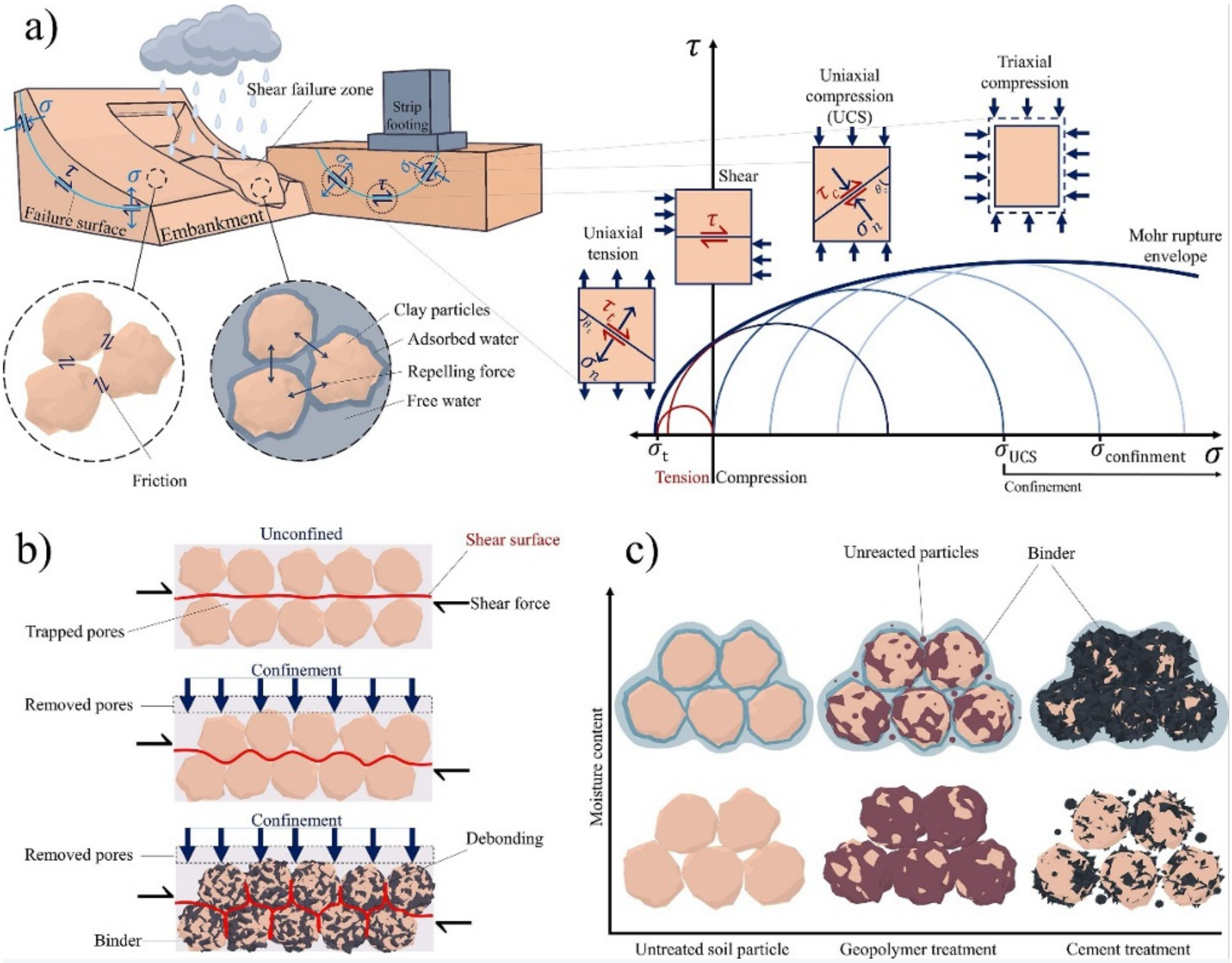

**Figure 4.** Schematic diagram of (a) stress distribution at failure surfaces of geotechnical profiles, (b) confinement effect on shear surface development in untreated and treated soil, (c) performance of binders at different curing conditions (Source: Pooria Ghadir et. al 2021)

## 3. Applications of Sustainable Soil Stabilization in Defense

The below table-1 explains in brief the possible application and effect of the MICP, biopolymer, and geopolymer soil stabilization.

**Table 1.** Defence application area for MICP, Biopolymer, and Geopolymer

| Application Area | MICP | Biopolymers | Geopolymers |
|---|---|---|---|
| **Bunker Reinforcement** | Increases soil shear strength, enhancing earth-covered bunker durability. | Facilitates rapid vegetation growth for camouflage and surface stability of earthen barriers. | Provides high-impact resistance and protection against environmental wear for long-term fortifications. |
| **Protective Barriers** | Improves soil resistance to erosion and shoring for trench support systems. | Enables quick construction of revetments and HESCO barriers in forward operating bases. | Used in creating robust blast walls capable of withstanding explosive forces. |
| **Rapid Deployment Roads** | Solidifies in-situ soils, creating a stable base for temporary roadways. | Ideal for dust suppression and immediate soil stabilization, crucial for convoy paths. | Forms a hard-wearing surface, suitable for heavy vehicle traffic and persistent use. |
| **Runway Repair** | Seals fissures and reinforces pavement bases against jet blast erosion. | Used for immediate surface repair, enabling continued aircraft operations. | Provides a long-lasting repair solution for concrete slabs subjected to repeated aircraft loading. |
| **Field Installation Foundations** | Stabilizes loose soils for quick erection of mobile command posts and satellite communication arrays. | Offers swift terrain reinforcement for setting up supply depots and medical stations. | Delivers a solid base for the construction of semi-permanent facilities and equipment pads. |
| **Ammunition and Fuel Storage** | Enhances ground support capacity, preventing subsidence under heavy loads. | Provides spill containment with impermeable lining for fuel and chemical storage areas. | Constructs blast-resistant containment structures for increased safety in ammunition depots. |
| **Bridge Construction** | Used in grouting applications for immediate support of temporary bridge abutments. | Assists in quick soil compaction for bridge approaches and exit paths. | Manufactures precast bridge elements, enabling rapid assembly and deployment in the field. |
| **Expeditionary Shelters** | Enhances load-bearing capacity for rapid-assembly shelters in remote locations. | Forms a quick-hardening surface for temporary flooring and weatherproofing. | Creates durable, lightweight panels for assembly of semi-permanent structures in harsh environments. |
| **Flood and Erosion Control** | Applied for riverbank stabilization near temporary bridges or forward bases. | Used in fabricating water barriers and flood walls for emergent water control. | Fabricates precast modular blocks for immediate response to breach events or rising water levels. |
| **Underground Facilities** | Improves ground cohesion to facilitate subterranean command center construction. | Stabilizes tunnel entrances and emergency egress points. | Serves as an encapsulating medium for the protective casing of underground utilities and communication lines. |
| **Helipad Construction** | Provides a solid foundation for temporary helipads in uneven terrain. | Acts as a bonding agent for helipad surfacing, resistant to rotor wash and wear. | Utilized for fast-setting helipad surfaces that can be quickly disassembled and moved. |
| **Blast Mitigation** | Interacts with soil to reduce the vulnerability of structures to seismic and blast-induced liquefaction. | Enhances the shock absorption characteristics of soil, reducing the transmission of blast forces. | Offers superior resistance to compression and shearing forces encountered in blast events. |
| **Surface Hardening** | Can be injected into subgrade layers to harden surfaces for heavy equipment storage areas. | Applied as a topical treatment to harden ground surfaces in vehicle maintenance areas. | Forms a chemically resistant surface, suitable for areas with potential chemical spills. |
| **Radiation Shielding** | Potential for encapsulating radioactive materials in situ due to calcite's radiation-dampening properties. | May serve as a secondary containment layer for radiation attenuation in temporary storage areas. | Possesses the capacity for high-density formulations that provide effective radiation shielding. |

As the above table discusses the effects of various environmentally friendly methods of stabilization, table 2 below explains the comparative impact, speed, and cost-effectiveness of these methods concerning cement. Table 2 synthesizes findings from previous reports and literature, comparing soil stabilization techniques in terms of compressive strength, environmental impact, cost-effectiveness, and application speed. It indicates that while MICP and geopolymers offer high compressive strengths with varying environmental impacts, biopolymers balance moderate strength with minimal environmental footprint and high cost-efficiency. Cement, although high in strength, also carries a significant environmental impact.

**Table 2.** Comparative Properties of Soil Stabilization Techniques

| Technique | Compressive Strength | Environmental Impact | Cost-Effectiveness | Application Speed |
|---|---|---|---|---|
| MICP | High | Low | Medium | Medium |
| Biopolymers | Medium | Very Low | High | High |
| Geopolymers | Very High | Medium | Medium | Low |
| Cement | High-Very High | Very High | Medium | Hign |

## 5. Challenges and Future Directions

While promising, these technologies face challenges such as scalability, cost, and integration into existing military logistics frameworks. Ongoing research focuses on optimizing these materials for broader applications, reducing costs, and improving performance under a variety of environmental conditions.

## 6. Conclusion

This study underscores the transformative potential of Microbially Induced Calcite Precipitation (MICP), biopolymers, and geopolymers in military infrastructure, highlighting their advantages over traditional materials like cement. These innovative soil stabilization methods enhance operational flexibility, enable rapid deployment, and significantly reduce environmental impact. By integrating these sustainable technologies, military operations can achieve greater efficacy and environmental responsibility, paving the way for advanced, eco-friendly defense strategies. Continued research and adoption are essential to fully realize their potential and promote sustainability in military contexts.

## Statements and Declarations

The authors declare that there is no conflict of interest regarding the publication of this paper. No external funding was received for the research conducted. Language models, including large language models (LLMs), were employed reasonably within the research process for language refinement and to assist in data analysis, under the guidelines for responsible AI use.

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